



Invited research article

Sustained growth of high mountain lakes in the headwaters of the Syr Darya River, Central Asia

Guoxiong Zheng^{a,b}, Anming Bao^{a,*}, Junli Li^a, Guoqing Zhang^{c,d}, Hongjie Xie^e, Hao Guo^{a,b}, Liangliang Jiang^{a,b}, Tao Chen^{a,b}, Cun Chang^a, Wenfeng Chen^{b,c}^a State Key Laboratory of Desert and Oasis Ecology, Institute of Ecology and Geography, Chinese Academy of Sciences, Xinjiang 830011, China^b University of Chinese Academy of Sciences, Beijing 100049, China^c Key Laboratory of Tibetan Environmental Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China^d CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing 100101, China^e Laboratory for Remote Sensing and Geoinformatics, University of Texas at San Antonio, San Antonio, TX 78249, USA

ARTICLE INFO

Keywords:

Glacial lake
Lake dynamics
Glacial melt
Outburst floods
Central Asia

ABSTRACT

The continuous rise in summer temperature and consequent glacier wastage have led to a significant loss of frozen water resources in the mountain headwaters of the major river systems in Central Asia. High mountain lakes in the headwaters of the Syr Darya River serve as sensitive indicators of climate change in the region. In this study, lakes in the headwaters of the Syr Darya River are examined using a Landsat image series. A total of 959 lakes covering a total area of $328.39 \pm 5.51 \text{ km}^2$ were identified in 2015, of which 91% were distributed in the larger Naryn River basin, and the remaining lakes were in the smaller Kara Darya River basin. During the period of the 1990s to 2015, a clear expansion trend in both lake area ($+6.64 \text{ km}^2$) and number of lakes ($+205$) was observed. Glacial lakes contributed 69% of the increase in the number of lakes. Among the four lake types, proglacial lakes showed the fastest area expansion with an average relative growth rate of 94% from the 1990s to 2015, 5–8 times that of the other three lake types: nonglacial lakes, unconnected-fed lakes and unconnected-nonglacial lakes. Lake Petrov was the fastest growing glacial lake ($+0.05 \text{ km}^2 \text{ yr}^{-1}$) during the past century and will continue to expand as its supply glacier continues to retreat. The continuous expansion and potential outburst risk of the Lake Petrov poses a serious threat to downstream toxic tailing ponds of the Kumtor Gold Mine. Lake Song Kol, the largest natural lake in this region, presented a steady status during 1972–2017. The warming climate-caused acceleration of glacial melt is thought to be the primary reason for the lake enlargements in this region. The lake inventory prepared here is valuable baseline dataset for the evaluation of water resources in the Syr Darya River drainage basin and for the potential risk and hazard assessments of glacial lake outburst floods.

1. Introduction

Climate change is gradually affecting the status of hydrology and water resources in most of the world's river source areas. Central Asia is a typical region due to the influence from the dominant Westerlies with the contributions from the East Asian and Indian monsoons (Chen and Huang, 2017). This characteristic atmospheric circulation combined with its unique geographical location makes Central Asia and its surrounding areas, such as Tibetan Plateau, one of the most ecologically and environmentally fragile areas worldwide. Outside the high altitude areas, most of Central Asia is characterized by arid and semiarid conditions. The shortage of water resources is a severe challenge in this region and is also a hot topic in the international research community

(Chen et al., 2016; Ososkova et al., 2000; Schone et al., 2018; Siegfried et al., 2011; Unger-Shayesteh et al., 2013). As the two largest rivers in Central Asia, both the Amu Darya River and the Syr Darya River terminate in the Aral Sea, and water shortages and water securities in their middle and lower reaches are highlighted after the collapse of the former Soviet Union in 1991 due to unreasonable management, allocation and even conflicts on the water resources of these two transboundary rivers between the upstream countries (Kyrgyzstan and Tajikistan) and downstream countries (Kazakhstan, Turkmenistan and Uzbekistan) (Schone et al., 2018; Soliev et al., 2015). A projection from White et al. (2014) indicates that the summer air temperature in the Amu Darya River catchment will increase by up to 5°C in 2070–2099 under a high-emission scenario relative to 1961–1990, and then the

* Corresponding author.

E-mail address: baoam@ms.xjb.ac.cn (A. Bao).<https://doi.org/10.1016/j.gloplacha.2019.03.004>

Received 21 September 2018; Received in revised form 20 February 2019; Accepted 5 March 2019

Available online 08 March 2019

0921-8181/ © 2019 Elsevier B.V. All rights reserved.

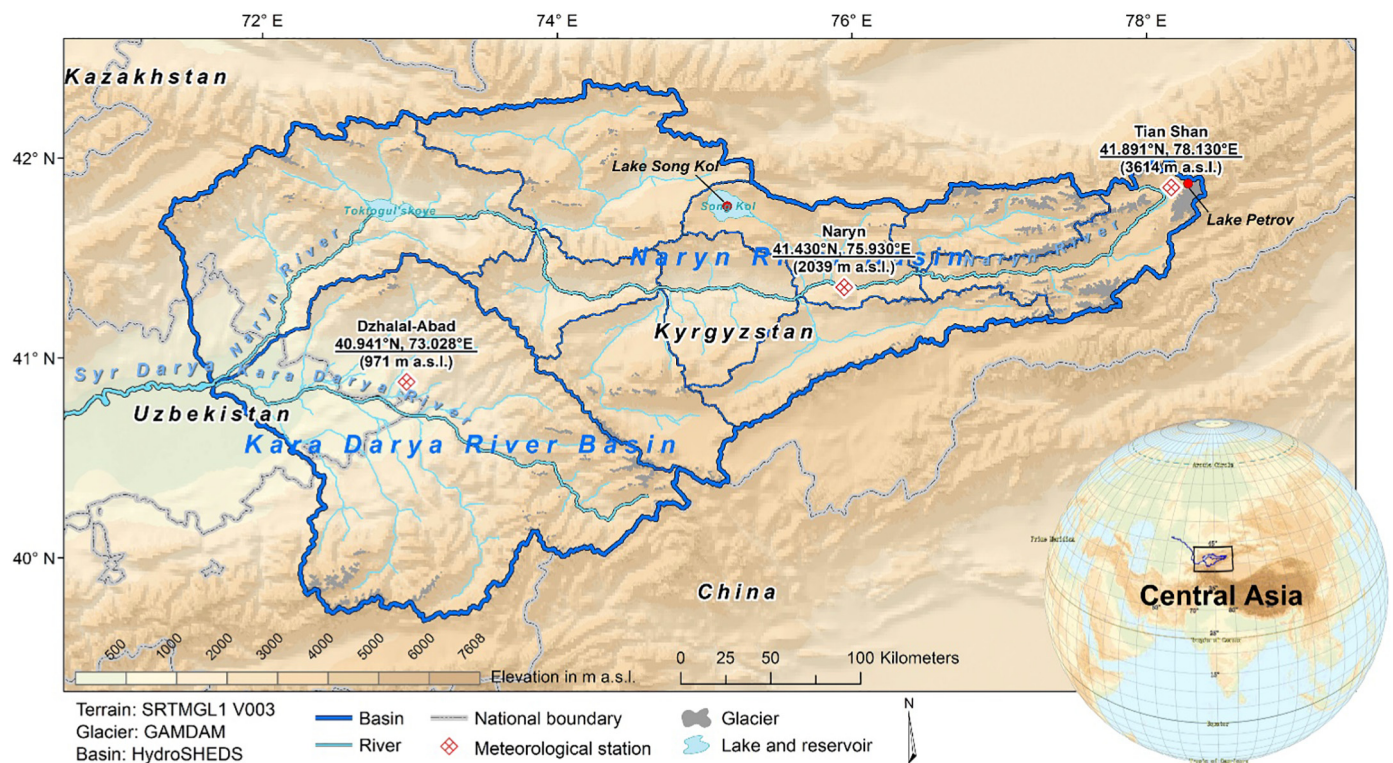


Fig. 1. Geographic locations of the headwaters of the Syr Darya River in Central Asia, including the Naryn River basin to the north and the Kara Darya River basin to the south.

seasonal precipitation is likely to change, which will increase agricultural water requirements by 10.6–16.0%, and nearly 34–49% of the irrigated land would become unirrigated land. Meanwhile, this prediction also reveals that the river runoff of the Amu Darya River, mostly supplied by glacial and snow meltwater, will also decrease by 10–20% due to this increased temperature. As the second largest drainage basin in Central Asia after the Amu Darya River basin, the Syr Darya River basin is facing a similar misfortune (Wegerich et al., 2015). Accelerated glacial meltwater will increase the river runoff over the short term, but ultimately, runoff could decline once a major part of the glacierised area melts away (Sorg et al., 2014).

High altitude cryosphere environments have spawned numerous alpine lakes worldwide. Changes in the cryosphere, including glacial ice, seasonal snow cover, and permafrost thickness are used as ideal indicators of climate change (Sorg et al., 2012; Zhang et al., 2017a). Changes in alpine lakes, especially changes in glacial lakes, can largely reflect the changing trends of the cryosphere in the region and indirectly indicate the characteristics of climate change as these regions are often less susceptible to human activities. For lakes located in the source areas of large rivers, their changes also reflect the status of river runoff and hydrological processes to some extent. The summer ablation and the possible combined effects of global warming and atmospheric circulation changes over the north Atlantic and north Pacific has led to a glacier mass loss of 270 ± 140 Gt and glacier area losses of 2960 ± 1030 km² in Tian Shan Mountains, Central Asia during 1961–2012, and this rate is almost four times the global average (Farinotti et al., 2015). The most dramatic glacial shrinkage has been observed in the outer and low-altitude ranges of the Tian Shan Mountains, which are densely populated and snow and glacial melts are particularly important for regional water resources (Sorg et al., 2012). The glacial area has decreased by 19% in the Pskem region, 12% in the Ili-Kungöy region, 12% in the At-Bashy region and 9% in the SE-Fergana region between ~1970 and ~2000 (Narama et al., 2010). The pervasive glacial wastage has resulted in the growth of the number and size of high mountain lakes, especially for glacially fed lakes. The

observed results from Wang et al. (2013) indicated that the total area of glacial lakes has expanded greatly, with an average rate of $0.8 \pm 0.1\%$ yr⁻¹ in the Tian Shan Mountains from 1990 to 2010. Monitoring in the adjacent Tarim River basin also shows an expanding trend with an average growth rate of 0.67% yr⁻¹ in 1990–2013, and the rate in 2000–2013 is four times greater than that of 1990–2000 (Wang et al., 2016). In addition, nearly 40.8% of all glacial lakes in the headwaters of the Amu Darya River experienced strong growth during 1968–2009 (Mergili et al., 2013).

In general, several recent studies have revealed the status and changes in lakes in most high mountainous regions in Central Asia (Daiyrov et al., 2018; Haemmig et al., 2014; Komatsu and Tsukamoto, 2017; Semakova et al., 2015; Zhang et al., 2018). Most of these studies have focused on the spatiotemporal evolution of glacial lakes and the assessment of potential glacial lake outburst floods (GLOFs) risk and hazard. In addition, most lake inventories only focus on lake changes near the glaciers, i.e., a glacier buffer of 10 km (Wang et al., 2013). In the catchment of the Syr Darya River, glacial lakes are nearly situated in the source areas, including the two major river basins of the Naryn River and Kara Darya River. In addition, many nonglacial natural lakes are also distributed in this region at different altitudes. However, the present status and changes in these lakes remain unclear until recently in this region, particularly for glacial lakes. Therefore, the aim of this study is to (1) present the first consistent high mountain lakes inventory in the headwaters of the Syr Darya River using the Landsat optical image series; and (2) reveal the trends and evolution characteristics of different lake types at five discrete episodes (1990s, 2000, 2005, 2010 and 2015).

2. Study area, materials, and methods

2.1. Study area

The headwaters of the Syr Darya River are primarily composed of the Naryn River in the north and the Kara Darya River in the south

(Fig. 1). The Naryn River originated in the Chesker Ayala and Ak-shiirak massif in the central Tian Shan Mountains and displayed mostly glacial and snow meltwater feeding (Bocchiola et al., 2017; Sorg et al., 2014). The Naryn River flows westward almost 807 km from east Kyrgyzstan to east Uzbekistan and finally enters the Fergana Valley. The Naryn River is supplied by many tributaries and drains a watershed area of $5.91 \times 10^4 \text{ km}^2$. The Kara Darya River is created by the confluence of the Kara-Kulja River and the Tar River, which flow from the Fergana Mountains and the Alai Mountains in Kyrgyzstan. The Kara Darya River drainage area is $3.01 \times 10^4 \text{ km}^2$, with a length of 177 km. The Kara Darya River also flows into the Fergana Valley across the eastern Osh Province of Kyrgyzstan. In the Fergana Valley, the Kara Darya River converges with the Naryn River, and the Syr Darya River is formed, which is the longest river in Central Asia.

This region is characterized by a typical continental climate with hot summers and cold winters (Bocchiola et al., 2017; Guo et al., 2018). The mean air temperature is 15 to 17 °C in July and – 15 to – 18 °C in January. The annual precipitation ranges from 200 to 800 mm at the relatively flat western Ferghana Valley and is > 1000 mm at the higher altitude eastern Tian Shan Mountains. High altitude areas in the study area are covered with snow all year round and with a total of 2737 glaciers covering an area of 1283 km² (Nuimura et al., 2015). The river recharge is mainly a mixture of precipitation, glacial and snow meltwater. The water level starts to rise in May and reaches its maximum in July or August. Lake Song Kol is the largest lake among many natural lakes in this region (Fig. 1) and is also the largest freshwater lake in Kyrgyzstan. Lake Petrov is the largest glacial lake in this basin, which is located in front of the Glacier Petrov on the northwestern slope of the Ak-shiirak massif (Fig. 1), and the lake developed in the basin of intermorainal depression after the retreat of the Glacier Petrov (Janský et al., 2008). Lake Petrov is close to the Kumtor Gold Mine and presents a potential outburst risk due to the unstable ice-moraine dams and active thermokarst processes, which will directly threaten the Kumtor tailing ponds 7 km downstream (Kutmanova and Satke, 2015).

2.2. Datasets

2.2.1. Satellite data

A total of 128 Landsat-5 Thematic Mapper (TM), Landsat-7 Enhanced Thematic Mapper Plus (ETM+) and Landsat-8 Operational Land Imager (OLI) scenes were used to monitor the changes and dynamics in high mountain lakes at the headwaters of the Syr Darya River. These images were freely obtained from the U.S. Geological Survey website (<https://glovis.usgs.gov/>) and covered five periods of the 1990s, 2000, 2005, 2010 and 2015 (Fig. 2). Due to the limited number and unsatisfactory quality of available images in these high mountain regions with prevalent cloud-cover conditions, images with

± 1 -year intervals were selected for each period, and the time span for the period of the 1990s was extended to 1994. Both the 1990s and 2010 are Landsat TM images, and 2015 is Landsat OLI scenes. Most selections in 2000 and 2005 are the Landsat ETM+ scenes coupled with a small amount of Landsat TM images (Fig. 2). All selected images were acquired from May to October, of which 92% were obtained from July to September when the lake water level was the highest. Selecting images of similar months during different periods is important to reduce the uncertainty in lake area change analysis due to seasonal variations. The original Landsat images were first layer-stacked and then converted from digital numbers (DNs) to top of atmosphere (TOA) reflectance using the gains, offsets, solar irradiance, sun elevation and acquisition time defined in the metadata file of each corresponding Landsat image. The Landsat ETM+ and OLI scenes with high-resolution panchromatic band were fused to improve the spatial resolution from the initial 30 m to 15 m based on a nearest neighbour diffusion pan sharpening algorithm (Sun et al., 2014). Although all Landsat ETM+ scenes collected since May 31, 2003 contain data gaps due to scan line corrector (SLC) failure, the images acquired in “SLC-off” mode still cover approximately 75% of the data for any given scene at the same high level of accuracy and precision as it did before the anomaly. These missing data can be compensated by using multitemporal scenes and thus have little impact on lake mapping for 2005 because the lake size in the study area is relatively small.

The altitudes of high mountain lakes are derived from the NASA 30-m SRTM digital elevation model (DEM) using the centroid coordinates of each lake as a reference. The basin extents were downloaded from the HydroSHEDS (Lehner and Grill, 2013). The river systems were extracted using the soil and water assessment tool (SWAT) based on the DEM data above.

2.2.2. Climatic data

The Climatic Research Unit (CRU v4.01) temperature and precipitation variables were utilized to analyse the climate trends in this study (Harris et al., 2014). Three meteorological stations, Tian Shan, Naryn and Dzhahal-Abad, located at different altitudes (Fig. 1) and with long-term observation records, were selected for climate element analysis and validation. However, because of the limited conditions to obtain continuous observational data from the same source, we integrated the meteorological observations from two different sources and eventually constructed a set of long-term monthly temperature (1965–2015) and precipitation (1965–2000/2005) datasets. The temperature and precipitation records for the Tian Shan and Naryn stations (1965–2005) and Dzhahal-Abad station (1965–2000) were derived from CAD (2010). The temperature records for the remaining time of the three stations were obtained from the Global Surface Summary of the Day (GSOD) issued by NOAA.

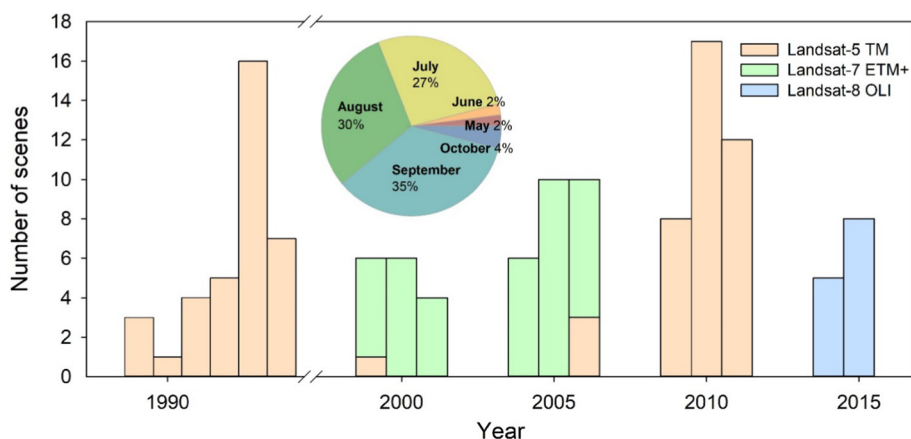


Fig. 2. Statistics of the five Landsat dataset periods used for high mountain lake mapping at the headwaters of the Syr Darya River.

2.3. Methods

2.3.1. Lake delineation

Numerous nearly automatic or semiautomatic methods for extracting Earth's surface water body from satellite images have been developed (Feyisa et al., 2014; Li and Sheng, 2012; Matsuoka et al., 2016; Verpoorter et al., 2012; Zhang et al., 2017c) and present a growing trend, particularly with the recent emergence of new technologies such as big data exploration and machine learning (Chen et al., 2017; Pekel et al., 2016). Although these methods can efficiently separate water body from other surface features, the amount of manual post-processing required would most likely offset the advantages of these automated methods due to the harsh weather environment and topographic effects in the high mountain areas (Mergili et al., 2013), as well as the relatively small size of most lakes in the study area. Hence, the lake extents were delineated using a consistent manual digitization procedure by a single operator with the standard Landsat false colour composite images (NIR, Red, Green bands as RGB) in this study. The minimum mapping unit was set to 2000 m², which is approximately 3 pixels for the Landsat TM scenes (Wang et al., 2013) and 9 pixels for pan-sharpened Landsat ETM+ and OLI images (Nie et al., 2017).

2.3.2. Lake classification

In this study, all identified lakes were classified into four types (see Table 1). First, lakes were divided into nonglacial lakes and glacial lakes according to whether the formation of the lake basin is controlled or affected by modern glaciation. Nonglacial lakes refer to lakes that are far from modern glaciers, and no obvious glacial residue covers the lake or exists around it, such as moraines. Glacial lakes are usually situated at the ends and sides of the glacier or not far downstream of the glacier and they are predominantly created due to the advance or retreat of the glacier with obvious glaciation characteristics. The nonglacial lakes primarily include natural lakes (excluding glacial lakes), artificial lakes and some perennial ponds that are larger than the selected minimum mapping unit. It is difficult to clearly define different types of glacial lakes due to the complex and diverse interaction processes between glaciers and lakes. Here we preliminarily define the lakes within the 10 km glacier buffer zone as glacial lakes and further divide them into three types based on the relationship between these lakes and their supply glaciers (Nie et al., 2017; Wang et al., 2013; Zhang et al., 2015). The most common type is the proglacial lake, which is in direct contact with its supply glaciers. Proglacial lakes directly receive the meltwater recharge of its supply glaciers and are extremely sensitive to regional cryosphere and climate change. The other two types are lakes that are not directly connected to glaciers and include lakes that do and do not receive glacial meltwater supply (hereinafter abbreviated as “unconnected-fed” and “unconnected-nonfed” lakes, respectively). Multi-temporal remote sensing data and historical high-resolution Google Earth™ images with different three-dimensional views were used to

recognize and collect additional information about lakes such as lake types. In addition, for identified nonglacial lakes in the buffer zone and glacial lakes outside the buffer zone were corrected through manual visual interaction discrimination.

2.3.3. Lake dynamics

To trace the dynamics of high mountain lakes, a unique code was assigned to the same lake in different periods. The time fields of the 1990s, 2000, 2005, 2010 and 2015 were added to the attribute table for each period within the ArcMap 10.2 platform. Three values of −1, 0 and 1 were assigned to these time fields depending on the current state of the lake during this period. The value of 0 was assigned to the lake if it did not exist during a given period, and 1 was assigned if the lake was present and the area is greater than the minimum mapping unit. For detecting the absolute variations in the number of lakes, a value of −1 was assigned to the lakes where the lake area is smaller than the minimum mapping unit but did not disappear.

Newly appeared lakes are defined as lakes that did not appear during the first two periods (time fields are 0, logical operator: and) and existed during the latter three periods (time fields are −1 or 1, logical operator: or). Extinct lakes refer to lakes that were present during the first two periods (time fields are −1 or 1, logical operator: or) but vanished during the latter three periods (time fields are 0, logical operator: and). For lakes that existed during all five periods (time field is 1 for all five periods), the linear regression method was used to determine the increasing and decreasing trends of the lake area. In this study, both 90% and 95% confidence levels were used. Lakes with a linear trend > 0 are defined as expanding lakes, and those < 0 are defined as shrinking lakes under the above confidence levels.

2.3.4. Uncertainty in lake area measurements

The uncertainty in lake area measurements is primarily attributed to the spatial resolution of the selected images (Wang et al., 2016). Images with high spatial resolutions can effectively reduce the uncertainty in lake delineations compared with images with low spatial resolutions. The uncertainty caused by the spatial resolution can be estimated as an error of ± 0.5 pixels on either side of the delineated lake outline (Fujita et al., 2009; Petrov et al., 2017; Zhang et al., 2017b). Here, half a pixel is 15 m for the Landsat TM scene and 7.5 m for the pan-sharpened Landsat ETM+ or OLI image. Because the selected Landsat products were processed with the standard terrain correction (Level 1 T) and the lakes are usually situated in flatter areas, we assumed that the georeferencing errors have a negligible impact on lake area measurements (Petrov et al., 2017). In addition, the poor visibility of lakes induced by clouds (shadows), snow cover and terrain shadows might also lead to uncertainty in lake area measurements. These conditions can be avoided using multitemporal scenes. Specifically, the number of images used in the 1990s, 2000, 2005, 2010 and 2015 is 4.5, 2.0, 3.3, 4.6 and 1.6 times the number of scenes (8 scenes) needed to cover the entire

Table 1
Lake types distinguished in this study and examples.

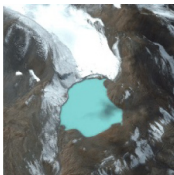
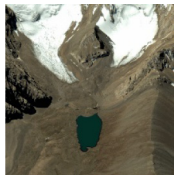
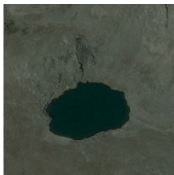
Lake type	Nonglacial lake	Glacial lake		
		Proglacial	Unconnected-fed	Unconnected-nonfed
Description	Far away from recent glaciers or the formation of the lake basin is not dominated by glaciation	Situated in the terminal or lateral of the glaciers and connected to its supply glaciers	Detached with supply glaciers but receives the glacial meltwater runoff recharge	Detached with supply glaciers and does not receive the glacial meltwater runoff recharge
Example				

Table 2Number and area ($\pm$ uncertainty) of different lake types at the headwaters of the Syr Darya River between the 1990s and 2015.

	1990s	2000	2005	2010	2015	1990s - 2015
Lake type	Number (Area, km ²)	Number (Area, km ²)	Number (Area, km ²)	Number (Area, km ²)	Number (Area, km ²)	Number (Area, km ²)
Glacial lake						
Proglacial	62 (3.65 $\pm$ 0.64)	70 (4.68 $\pm$ 0.40)	79 (5.24 $\pm$ 0.60)	84 (5.30 $\pm$ 0.80)	117 (5.87 $\pm$ 0.55)	55 (2.22)
Unconnected-fed	231 (5.15 $\pm$ 1.80)	271 (5.53 $\pm$ 1.03)	269 (5.72 $\pm$ 1.40)	264 (5.76 $\pm$ 2.02)	301 (6.04 $\pm$ 1.14)	70 (0.89)
Unconnected-nonfed	122 (1.96 $\pm$ 0.80)	138 (2.16 $\pm$ 0.49)	131 (1.90 $\pm$ 0.47)	130 (1.94 $\pm$ 0.82)	138 (2.04 $\pm$ 0.44)	16 (0.08)
Nonglacial lake	339 (310.99 $\pm$ 6.04)	365 (312.91 $\pm$ 3.48)	383 (312.43 $\pm$ 4.74)	414 (314.24 $\pm$ 6.82)	403 (314.43 $\pm$ 3.38)	64 (3.45)
Sum	754 (321.75 $\pm$ 9.27)	844 (325.28 $\pm$ 5.40)	862 (325.29 $\pm$ 7.21)	892 (327.24 $\pm$ 10.46)	959 (328.39 $\pm$ 5.51)	205 (6.64)

study area, respectively (Fig. 2).

3. Results

3.1. Basic statistics of lakes from the 1990s to 2015

3.1.1. Lake status and spatial distribution in 2015

A total of 959 lakes covering a total area of 328.39 ± 5.51 km² are outlined in 2015 (Table 2), and the spatial distributions of these lakes are presented in Fig. 3 according to lake type and size. The glacial lakes account for 58% of the total quantity and only 4% of the total area. Lake Song Kol, the largest lake in this basin, contributes 85% alone of the total lake area. The area of other remaining lakes is relatively small. The second largest lake, Lake Sary Chelek, occupies an area of

5.13 km², and the third largest lake is also the largest glacial lake, Lake Petrov, with an area of 4.05 km² in 2015. For the distribution of lakes in the two major sub-basins, the Naryn River basin holds 91% of the total number and 98% of the total area, and the Kara Darya River basin occupies a small remaining portion.

The lakes outlined in 2015 are distributed at an altitude range of 1389–4385 m with an average altitude of 3570 m and a median altitude of 3653 m (Fig. 4a–b). Approximately 80% of the lakes are located between 3162 m and 3995 m (Fig. 4d). The nonglacial lakes are distributed at various altitudes with the lowest average elevation of 3358 m (Fig. 4a–c). As the altitude increases, the number of glacial lakes also gradually increases. Most of the proglacial lakes (90%) range from 3365 m to 4235 m with the highest average elevation of 3857 m. Nearly 90% of unconnected-fed lakes occur in the interval between 3368 m

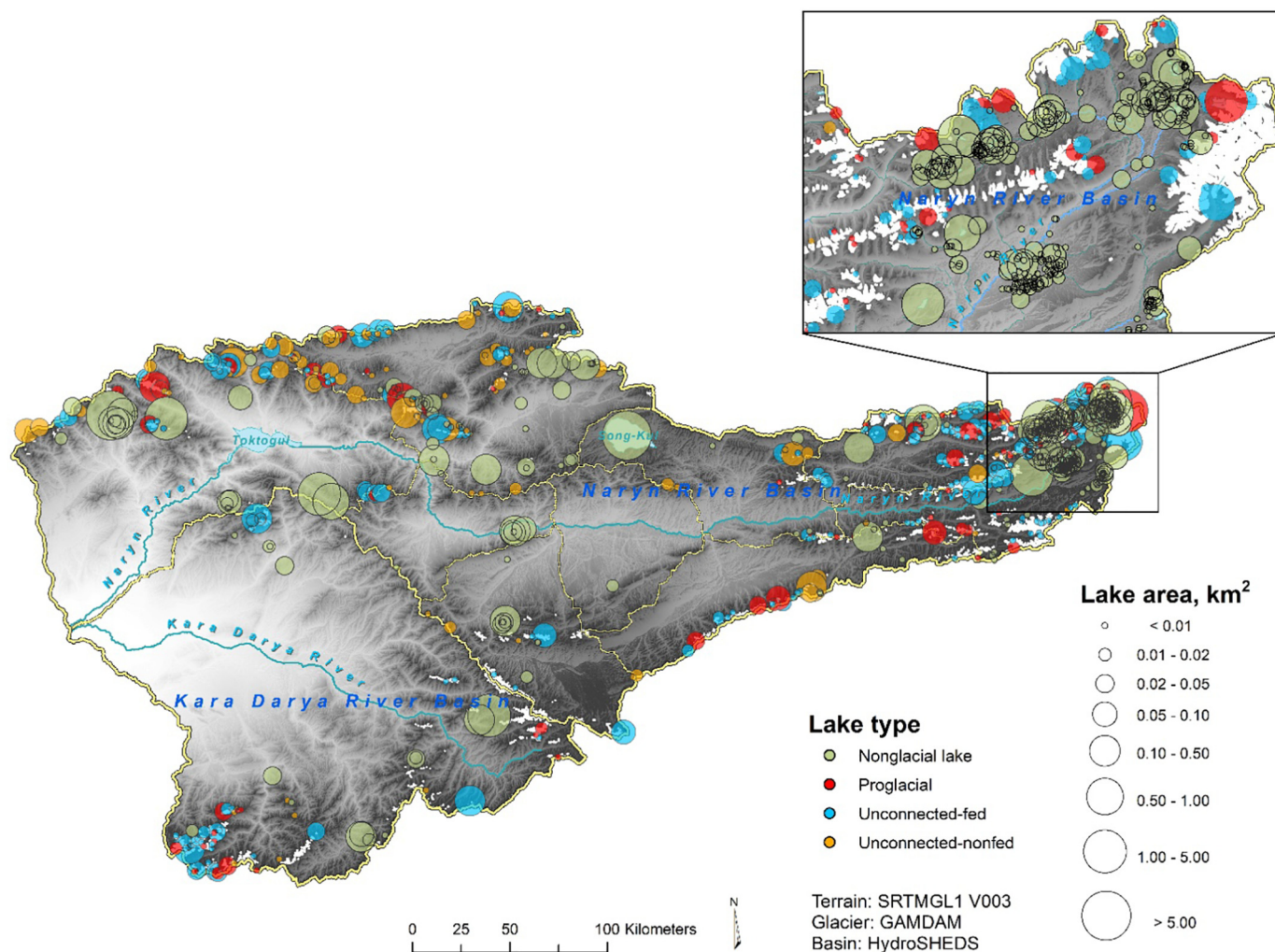


Fig. 3. Spatial distribution of high mountain lakes in the headwaters of the Syr Darya River in 2015 according to lake type and size.

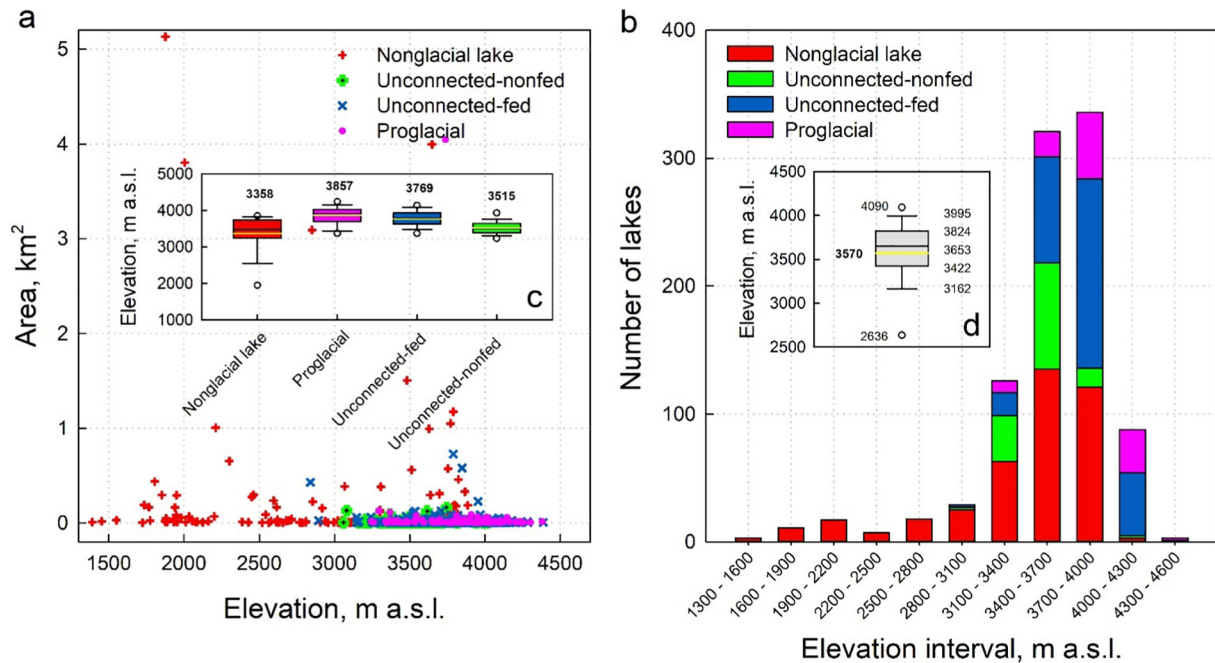


Fig. 4. (a) The distribution of individual lake elevation versus area for different lake types; (b) the stacked column of various lake types according to an elevation interval of 300 m a.s.l.; (c) the box-whisker plot of the elevation distribution of different lake types and (d) all lakes. These figures are based on the lake dataset in 2015. The average elevation of each lake type and all lakes in figure (c-d) is depicted with a yellow line and labelled in bold black numbers. Measures of elevation spread and center of all lakes include the median, interquartile ranges (25th and 75th percentiles), minimum and maximum (10th and 90th percentiles), and outliers (5th and 95th percentiles) are also labelled in figure (d). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and 4133 m with an average altitude of 3769 m. The average elevation of unconnected-nonfed lakes is 3515 m, which mainly occupies the altitude range of 3229–3926 m (90%) (Fig. 4c).

3.1.2. Continuously increasing numbers and areas

A clear growth trend in both total number and total area is observed (Table 2). Over the past 25 years, the total number of lakes has increased by 205, and the total area has expanded by 6.64 km². The glacial lakes increased by 141, including 55 proglacial lakes, 70 unconnected-fed lakes and 16 unconnected-nonfed lakes, accounting for 69% of all lakes that showed increases. The proglacial lake is the largest area-expanding lake type, with an area growth of 2.22 km², which is 2.5 times that of the unconnected-fed lakes and 27.8 times that of the unconnected-nonfed lakes. In general, the number of proglacial lakes shows a continuously increasing trend; proglacial lake numbers in the 1990s, 2000, 2005, 2010 and 2015 were 62, 70, 79, 84 and 117, respectively. The other three lake types showed an overall increasing trend but fluctuated during the observation periods. Specifically, they all show a clear increase in number and size in the first and last periods.

The time series change matrices for nonglacial lakes and glacial lakes are summarized in Table 3 and Table 4, respectively. Every possible lake change pattern has been considered. Based on it, the absolute changes in the number of lakes are calculated, which will help us to more objectively understand the changes in the number of lakes in this source area. For example, for the 61 glacial lakes identified in 2015 based on the minimum mapping unit, 31 of them have already existed at any one of the previous periods. However, these lakes are not included in the lake inventory in 2015 because their area is smaller than the defined minimum mapping unit in this period. In other words, the absolute increase in the number of glacial lakes in 2015 is 30 compared to the previous periods, and the remaining 31 glacial lakes are not compiled just because their area did not reach the defined threshold.

3.2. Changes in lake area and elevation

3.2.1. Area changes of different lake types during the 1990s–2015

To investigate the area changes in different lake types, the relative area change rates for lakes in the 1990s and 2015 were calculated and analysed in this section. Fig. 5a shows the area changes in individual lakes of different types. All four lake types show a positive relative average area change rate, and the area change rate of small lakes is higher than that of large lakes. Proglacial lakes have the highest relative average area change rate of 94%, which is approximately 5–8 times that of the other three lake types. The unconnected-fed lakes have the second highest relative average area change rate of 17%. From the area scale analysis in Fig. 5b, an area scale of < 0.01 km² has the highest positive relative average area change rate. Note that proglacial lakes show consistent positive change rates on all scales, with an obvious relative average area change rate of 160% on the smallest scale (< 0.01 km²). In addition to the size scale of 0.02–0.05 km² (with a relative average area change rate of –7%), the unconnected-fed lakes also show a higher growth rate in other intervals. There is only one proglacial lake (Lake Petrov) larger than 1 km²; thus, the area change rate of 55% for proglacial lakes in the size scale of > 1 km² is only attributed to Lake Petrov. The increased relative area change rate in proglacial lakes indicates that the glacial retreat at the headwaters of the Syr Darya River intensified during the 1990s–2015.

3.2.2. Elevation variations in different lake types between the 1990s and 2015

The accelerated glacial retreat will not only lead to further expansion of existing glacial lakes but also create new glacial lakes, especially proglacial lakes. With the recession of the glacier tongue, the lakes at the glacial terminus will advance accordingly; in other words, the altitudes of these proglacial lakes will change along with the recession of the glacier tongue. The elevation changes of different lake types during the five periods are presented in Fig. 6; no continuous increase in the elevation for different lake types is observed. However, the average

Table 3

Matrix of time serial changes in nonglacial lakes at the headwaters of the Syr Darya River from the 1990s to 2015.

Code	1990s		2000		2005		2010		2015	
	Number	Area (km ²)	Number	Area (km ²)	Number	Area (km ²)	Number	Area (km ²)	Number	Area (km ²)
1990s	6 (1)	0.067 ± 0.032	–	–	–	–	–	–	–	–
1990s-2000	4 (4)	0.014 ± 0.014	4 (4)	0.013 ± 0.006	–	–	–	–	–	–
1990s-2005	1 (1)	0.002 ± 0.003	–	–	1 (1)	0.003 ± 0.002	–	–	–	–
1990s-2010	3 (2)	0.009 ± 0.009	–	–	–	–	3 (2)	0.0110 ± 0.010	–	–
1990s-2015	1 (0)	0.003 ± 0.003	–	–	–	–	–	–	1 (0)	0.004 ± 0.002
1990s-2000-2005	2 (1)	0.006 ± 0.006	2 (1)	0.005 ± 0.003	2 (1)	0.006 ± 0.005	–	–	–	–
1990s-2000-2010	1 (1)	0.003 ± 0.003	1 (1)	0.003 ± 0.002	–	–	1 (1)	0.003 ± 0.003	–	–
1990s-2000-2015	2 (1)	0.005 ± 0.006	2 (1)	0.007 ± 0.004	–	–	–	–	2 (1)	0.005 ± 0.003
1990s-2005-2010	3 (3)	0.011 ± 0.010	–	–	3 (3)	0.012 ± 0.010	4 (3)	0.014 ± 0.014	–	–
1990s-2010-2015	3 (3)	0.011 ± 0.010	–	–	–	–	3 (3)	0.013 ± 0.011	3 (3)	0.012 ± 0.006
1990s-2000-2005-2010	10 (7)	0.043 ± 0.036	10 (7)	0.039 ± 0.017	10 (7)	0.038 ± 0.024	10 (7)	0.045 ± 0.039	–	–
1990s-2000-2005-2015	7 (6)	0.049 ± 0.031	7 (6)	0.054 ± 0.016	7 (6)	0.052 ± 0.020	–	–	7 (6)	0.04 ± 0.014
1990s-2000-2010-2015	13 (13)	0.05 ± 0.046	13 (13)	0.077 ± 0.028	–	–	13 (13)	0.068 ± 0.052	13 (13)	0.049 ± 0.023
1990s-2005-2010-2015	9 (7)	0.041 ± 0.033	–	–	9 (7)	0.038 ± 0.030	9 (7)	0.070 ± 0.041	9 (7)	0.048 ± 0.017
1990s-2000-2005-2010-2015	274 (0)	310.676 ± 5.798	275 (0)	310.092 ± 3.211	275 (0)	308.558 ± 4.152	275 (0)	309.521 ± 6.019	275 (0)	309.623 ± 3.027
2000	–	–	3 (3)	0.012 ± 0.005	–	–	–	–	–	–
2000-2005	–	–	3 (2)	0.016 ± 0.006	3 (2)	0.010 ± 0.010	–	–	–	–
2000-2010	–	–	4 (4)	0.016 ± 0.007	–	–	4 (4)	0.02 ± 0.015	–	–
2000-2015	–	–	7 (6)	0.019 ± 0.010	–	–	–	–	7 (6)	0.022 ± 0.011
2000-2005-2010	–	–	6 (2)	0.041 ± 0.015	6 (2)	0.044 ± 0.022	6 (2)	0.051 ± 0.028	–	–
2000-2005-2015	–	–	1 (1)	0.003 ± 0.001	1 (1)	0.002 ± 0.001	–	–	1 (1)	0.002 ± 0.001
2000-2010-2015	–	–	4 (3)	0.014 ± 0.007	–	–	3 (2)	0.013 ± 0.011	4 (3)	0.014 ± 0.007
2000-2005-2010-2015	–	–	23 (10)	2.499 ± 0.138	23 (10)	3.344 ± 0.284	23 (10)	3.938 ± 0.282	23 (10)	4.205 ± 0.133
2005	–	–	–	–	6 (5)	0.018 ± 0.014	–	–	–	–
2005-2010	–	–	–	–	11 (7)	0.049 ± 0.035	10 (6)	0.062 ± 0.043	–	–
2005-2015	–	–	–	–	1 (1)	0.002 ± 0.003	–	–	1 (1)	0.002 ± 0.001
2005-2010-2015	–	–	–	–	25 (11)	0.257 ± 0.126	25 (11)	0.229 ± 0.140	25 (11)	0.165 ± 0.063
2010	–	–	–	–	–	–	11 (10)	0.044 ± 0.041	–	–
2010-2015	–	–	–	–	–	–	14 (8)	0.139 ± 0.071	14 (8)	0.112 ± 0.031
2015	–	–	–	–	–	–	–	–	18 (9)	0.131 ± 0.044
Sum	339 (50)	310.989 ± 6.042	365 (64)	312.913 ± 3.478	383 (64)	312.432 ± 4.737	414 (89)	314.242 ± 6.821	403 (79)	314.434 ± 3.384

Note for Table 3 and Table 4. “Code” indicates the presence and absence of lakes during different periods. For example, code “1990s-2000” represents the lakes that existed only in 1990s and 2000 and then disappeared. The number in brackets indicates that the number of lakes still present, except that their area is smaller than the limited minimum mapping unit (2000 m²). For instance in 2000, the number “6 (1)” in code “1990s-2000” means that there are four lakes < 2000 m² in size but they did not disappear in 2000.

altitude has increased from the 1990s to 2015 for different lake types, with about 62 m for proglacial lakes, 22 m for unconnected-fed lakes and 2 m for unconnected-nonfed lakes. Interestingly, the nonglacial lakes have wider elevation ranges and greater volatility than the glacial lakes, which is probably because these lakes are affected by climatic factors as well as intense human activities, such as land use change and mineral exploration (Zhang et al., 2017a). Detailed statistics are listed in Table S1.

3.2.3. Lake changes in the two major river basins

Fig. 7 shows the changes in the number and area of different lake types in the two major river basins at the headwaters of the Syr Darya River. Taking the five periods altogether, the Naryn River basin contributed approximately 92% of the lake number and 98% of the lake area. Consistent with the growth trend of the number and area of lakes throughout the study area, the number and area of proglacial lakes in both drainage basins also show increasing trends. The number and (area) of proglacial lakes in the Naryn River basin increased from 59 (3.59 ± 0.62 km²) in the 1990s to 98 (5.67 ± 0.50 km²) in 2015, and in the Kara Darya River basin, the number and (area) increased from 3 (0.06 ± 0.02 km²) in the 1990s to 19 (0.21 ± 0.05 km²) in 2015. The number and area of the other three lake types showed fluctuating upward trends. The specific statistics are shown in Table S2.

Fig. 8 demonstrates the interannual area change of Lake Song Kol. It

remained relatively stable over the past 45 years with an average area of 279.91 km². In 1972, 1991, 2000, 2010 and 2017, the area was 280.98 ± 1.86, 279.21 ± 1.77, 279.40 ± 1.04, 278.53 ± 1.74 and 281.79 ± 0.94 km², respectively. The area change rate of Lake Song Kol is about 2% during the last half-century.

3.3. Dynamic evolution of different lake types

3.3.1. Newly appeared and extinct lakes

A total of 91 new lakes and 54 extinct lakes were identified (Fig. 9a-b). The corresponding examples are shown in Fig. 10a-b. The size of newly appeared lakes ranged from 0.002 to 0.06 km², with an average area of 0.007 km² and a total area of 0.66 km². The glacial lakes accounted for 65% of the 91 new lakes and 61% of the total area with the same average area of 0.007 km². Proglacial lakes contributed approximately 36% of the total quantity of newly appeared glacial lakes, with an average area of 0.009 km² and an elevated average altitude of 3972 m.

Of the 54 extinct lakes, 47 (87%) were glacial lakes, which accounted for 85% of the total disappeared lake area. The average altitude of these glacial lakes is 3868 m. Proglacial lakes occupy 22 of the extinct glacial lakes and are 67% of the total area. It is worth noting that the disappeared glacial lakes that are not directly connected to the glaciers are all the glacial-fed lakes (Fig. 9b). These lakes account for

Table 4

Matrix of time serial changes in glacial lakes at the headwaters of the Syr Darya River from the 1990s to 2015.

Code	1990s		2000		2005		2010		2015	
	Number	Area (km ²)	Number	Area (km ²)	Number	Area (km ²)	Number	Area (km ²)	Number	Area (km ²)
1990s	25 (8)	0.187 ± 0.111	–	–	–	–	–	–	–	–
1990s-2000	11 (3)	0.103 ± 0.055	11 (3)	0.110 ± 0.030	–	–	–	–	–	–
1990s-2005	2 (1)	0.007 ± 0.007	–	–	2 (1)	0.007 ± 0.004	–	–	–	–
1990s-2015	3 (2)	0.011 ± 0.010	–	–	–	–	–	–	3 (2)	0.009 ± 0.005
1990s-2000-2005	5 (3)	0.045 ± 0.026	5 (3)	0.032 ± 0.012	5 (3)	0.041 ± 0.013	–	–	–	–
1990s-2000-2010	2 (2)	0.009 ± 0.008	2 (2)	0.009 ± 0.004	–	–	2 (2)	0.005 ± 0.006	–	–
1990s-2000-2015	6 (5)	0.029 ± 0.023	6 (5)	0.022 ± 0.011	–	–	–	–	6 (5)	0.019 ± 0.010
1990s-2005-2010	1 (1)	0.004 ± 0.003	–	–	1 (1)	0.003 ± 0.001	1 (1)	0.003 ± 0.003	–	–
1990s-2005-2015	4 (4)	0.015 ± 0.013	–	–	4 (4)	0.015 ± 0.008	–	–	4 (4)	0.014 ± 0.008
1990s-2010-2015	2 (2)	0.009 ± 0.007	–	–	–	–	2 (2)	0.008 ± 0.007	2 (2)	0.006 ± 0.004
1990s-2000-2005-2010	13 (9)	0.075 ± 0.056	13 (9)	0.073 ± 0.027	13 (9)	0.064 ± 0.036	13 (9)	0.053 ± 0.047	–	–
1990s-2000-2005-2015	8 (6)	0.050 ± 0.035	8 (6)	0.047 ± 0.018	8 (6)	0.043 ± 0.028	–	–	8 (6)	0.038 ± 0.017
1990s-2000-2010-2015	10 (8)	0.032 ± 0.033	10 (8)	0.044 ± 0.021	–	–	11 (9)	0.042 ± 0.038	10 (8)	0.047 ± 0.020
1990s-2005-2010-2015	5 (3)	0.060 ± 0.031	–	–	5 (3)	0.023 ± 0.018	5 (3)	0.026 ± 0.021	5 (3)	0.038 ± 0.013
1990s-2000-2005-2010-2015	318 (0)	10.124 ± 2.814	318 (0)	11.533 ± 1.585	318 (0)	11.936 ± 2.026	317 (0)	12.013 ± 2.950	318 (0)	12.459 ± 1.606
2000	–	–	15 (11)	0.061 ± 0.028	–	–	–	–	–	–
2000–2005	–	–	8 (4)	0.033 ± 0.017	8 (4)	0.033 ± 0.018	–	–	–	–
2000–2010	–	–	4 (3)	0.016 ± 0.007	–	–	4 (3)	0.015 ± 0.015	–	–
2000–2015	–	–	14 (13)	0.045 ± 0.023	–	–	–	–	14 (13)	0.066 ± 0.027
2000–2005-2010	–	–	5 (3)	0.019 ± 0.009	5 (3)	0.024 ± 0.011	5 (3)	0.026 ± 0.021	–	–
2000–2005-2015	–	–	14 (13)	0.037 ± 0.020	14 (13)	0.040 ± 0.026	–	–	14 (13)	0.041 ± 0.022
2000–2010-2015	–	–	7 (5)	0.045 ± 0.015	–	–	8 (6)	0.030 ± 0.028	7 (5)	0.034 ± 0.015
2000–2005–2010-2015	–	–	39 (15)	0.243 ± 0.093	39 (15)	0.363 ± 0.123	39 (15)	0.387 ± 0.206	39 (15)	0.505 ± 0.117
2005	–	–	–	–	15 (15)	0.059 ± 0.034	–	–	–	–
2005–2010	–	–	–	–	3 (2)	0.012 ± 0.007	3 (2)	0.011 ± 0.010	–	–
2005–2015	–	–	–	–	12 (9)	0.035 ± 0.019	–	–	12 (9)	0.053 ± 0.024
2005–2010-2015	–	–	–	–	27 (9)	0.165 ± 0.099	27 (9)	0.189 ± 0.127	27 (9)	0.256 ± 0.077
2010	–	–	–	–	–	–	15 (5)	0.055 ± 0.052	–	–
2010–2015	–	–	–	–	–	–	26 (12)	0.138 ± 0.103	26 (12)	0.154 ± 0.058
2015	–	–	–	–	–	–	–	–	61 (31)	0.215 ± 0.104
Sum	415 (57)	10.758 ± 3.233	479 (103)	12.371 ± 1.920	479 (97)	12.861 ± 2.472	478 (81)	12.999 ± 3.635	556 (137)	13.953 ± 2.127

53% of the total number of extinct glacial lakes and 33% of the total disappeared area. The disappearance of lakes can be attributed to many factors and is a complex and independent process for each lake with many uncertainties. Generally, it is caused by the following reasons: (1) the intervention of human activities, especially for areas with dense

populations and extensive human activities; (2) possible GLOF events. The long-term series images can be utilized to identify the specific extinction time of the glacial lake but still need some additional literatures or field investigation to confirm. (3) the shortage or disappearance of recharge water sources, such as insufficient water supply due to long

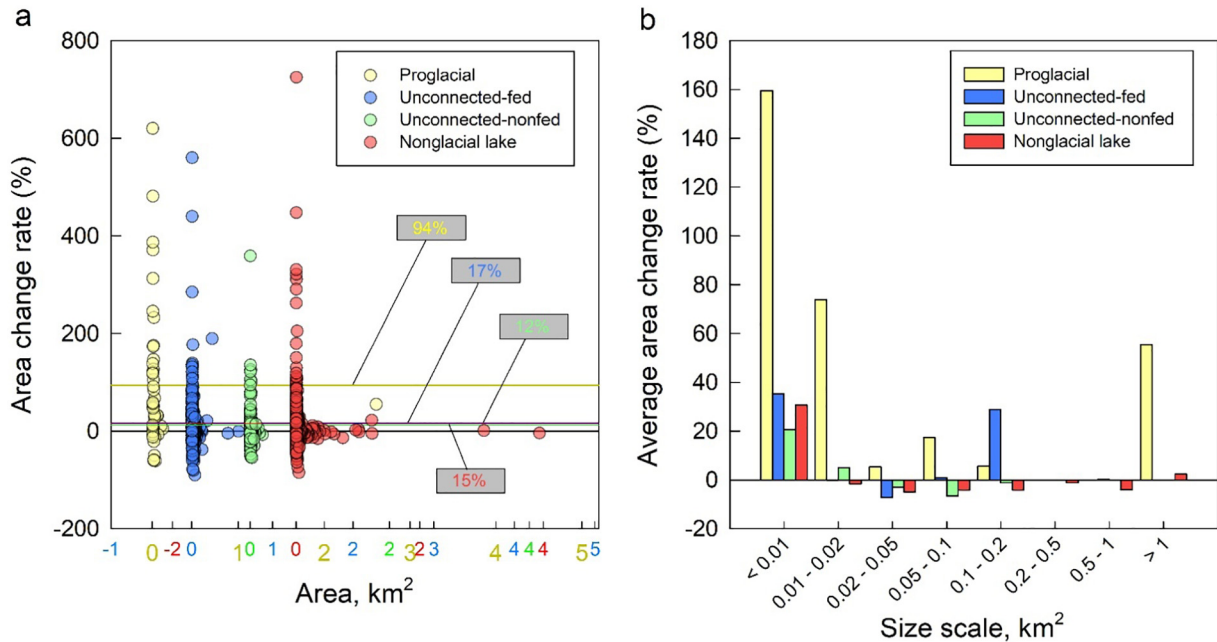


Fig. 5. Area changes of different lake types for (a) individual lake and (b) different size scales for the 1990s-2015. The numbers labelled in figure (a) are the average area change rates for each lake type. The x-axis of figure (a) was properly translated with different colours to indicate the corresponding lake type.

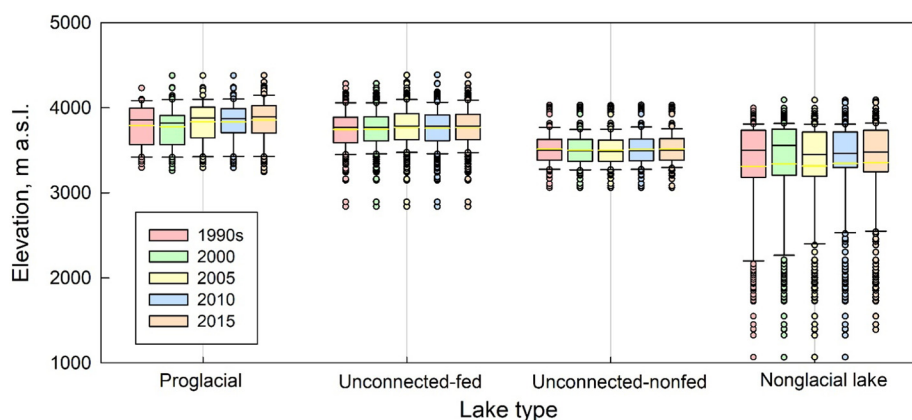


Fig. 6. Elevation variations of different lake types during the five periods. The yellow and black lines within each box are the average and median elevations for each lake type, respectively. The boundaries of the box indicate the 25th and 75th percentile, and the error bars below and above the box indicate the 10th and 90th percentiles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

periods of non-rainfall or insufficient glacial meltwater to replenish the lake due to the retreat or disappearance of the supply glaciers.

3.3.2. Expanding and shrinking lakes

For 591 high mountain lakes (274 nonglacial lakes and 317 glacial lakes) that appeared and existed during all five periods (Table 3 and Table 4), linear trend analyses were performed. Fig. 9c-d exhibit trends of expanding and shrinking lakes at the 90% significance level. Only 54 lakes showed a continuous growth trend, of which 32 are glacial lakes, accounting for 69% of the total increased area. In the upper part of the Naryn River basin, 70% of expanding lakes are situated. A total of 33 lakes were identified as having a continuously decreasing trend. Nonglacial lakes contributed 55% of the total number and 84% of the total

area. None of the proglacial lakes showed significant or continuous area reductions. Fig. 10c-d separately show examples of expanding and shrinking lakes. Overall, most of the lakes in this region did not show the characteristics of regular changes but changed in an irregular pattern (Fig. 10e). However, seasonal variations in high mountain lakes are intense, which will bring some errors to the analysis of lake evolution. Selecting images in optimal months for lake mapping can ensure the accuracy of lake change analysis (92% of selected images in this study are from July to September, see Fig. 2). Despite this, some images in non-optimal months are inevitably used due to the limited number and quality of images available.

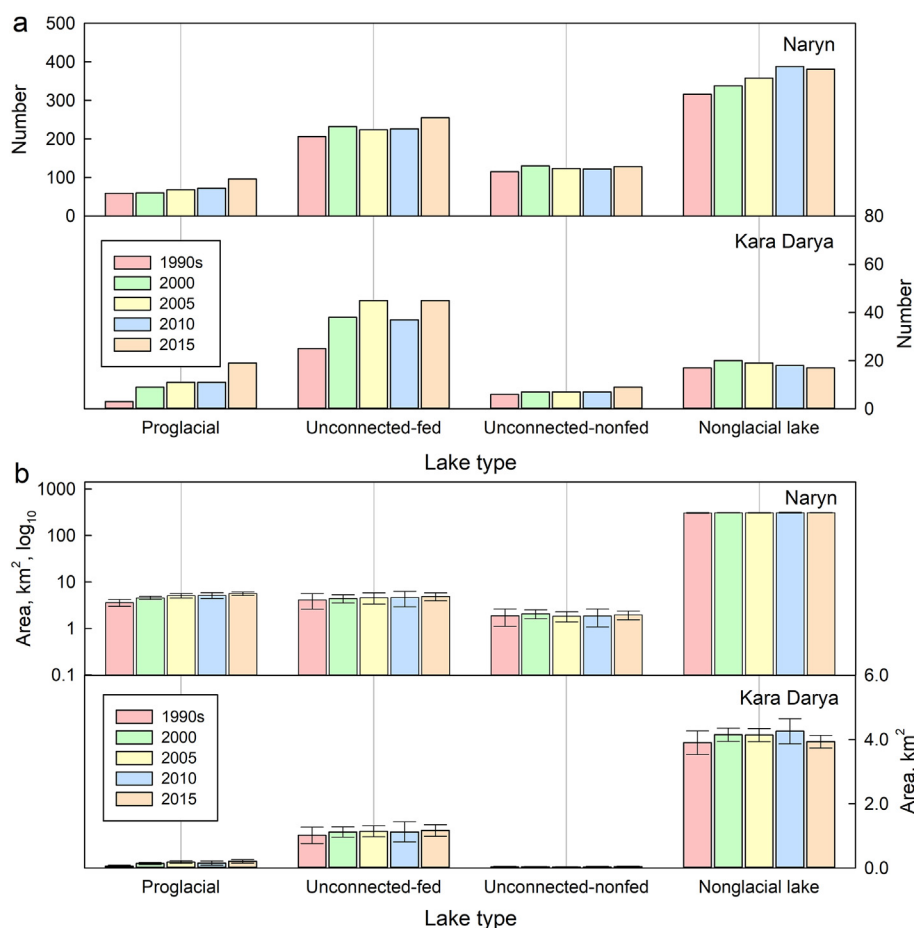


Fig. 7. Changes in the number (a) and area (b) of different lake types in the two major river basins (Naryn River basin and Kara Darya River basin).

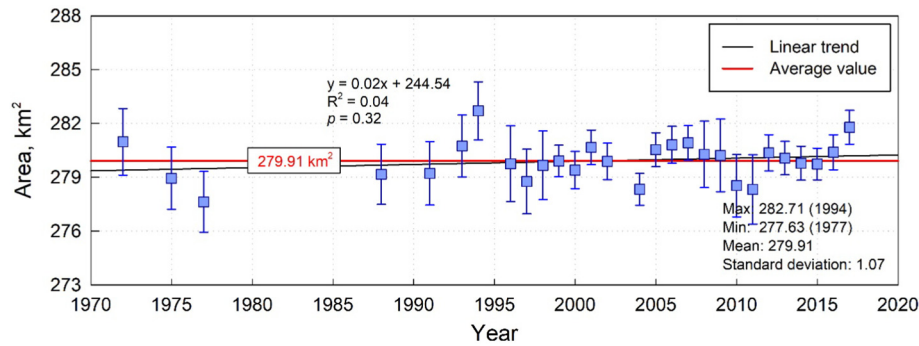


Fig. 8. Interannual variations in Lake Song Kol (41.839°N, 75.151°E), the largest natural lake in the study area, over the past 45 years. The error bars represent the lake area uncertainty measured from Landsat imagery.

3.3.3. Interannual variation of rapidly growing glacial lakes

The rapid and growing glacial lakes have potential GLOFs hazard and risk because the continued expansion of lake area may cause the lake dam to rupture or overflow and then form the GLOFs events, especially for ice-dammed and moraine-dammed lakes (Rounce et al., 2017). For the nine identified glacial lakes with the fastest growth rates ($p < .05$), their interannual variations were analysed (Fig. 9c and Fig. 11). Lake #1 (Lake Petrov) is the fastest growing lake with a growth rate of $0.05 \text{ km}^2 \text{ yr}^{-1}$. In 1911, the area of Lake Petrov was only $0.2\text{--}0.3 \text{ km}^2$ (Janský et al., 2008), and it increased to $4.11 \pm 0.15 \text{ km}^2$ in 2017, which is an increase of > 13 times in the past century. The area of Lake Petrov has expanded by more than four times since satellite images were available (1957, 0.96 km^2 , Janský et al., 2008). Lake #2 (here named Lake Karasay, in continuing with the naming convention of Lake Petrov) appeared in the early 1970s, with an area of $0.014 \pm 0.007 \text{ km}^2$ in 1973. Lake Karasay evolved into an area of $0.755 \pm 0.091 \text{ km}^2$ in 2017, and the average annual growth rate is 2%.

At the outset, the lake was connected to the terminus of the Glacier North Karasay (Fig. 13c) and later evolved into an unconnected-fed lake as its mother glacier shrank.

The other seven glacial lakes have smaller lake areas and growth rates. Lake #3 is expanding at a rate of $0.0015 \text{ km}^2 \text{ yr}^{-1}$. Lake #3 is a proglacial lake and appeared between 1980 and 1989, with an area of $0.015 \pm 0.007 \text{ km}^2$ in 1990 and an area of $0.056 \pm 0.008 \text{ km}^2$ in 2015 (Fig. 10c and Fig. 11c). In conjunction with Landsat MSS images available in the 1970s, Lakes #4–7 were likely developed in the 1980s. The growth rate of these lakes ranges from $0.0003\text{--}0.0008 \text{ km}^2 \text{ yr}^{-1}$. Detailed information on these lakes can be found in Table S3.

4. Discussion

4.1. The climate change driver of lake changes

Due to the harsh and inaccessible environment at high altitudes,

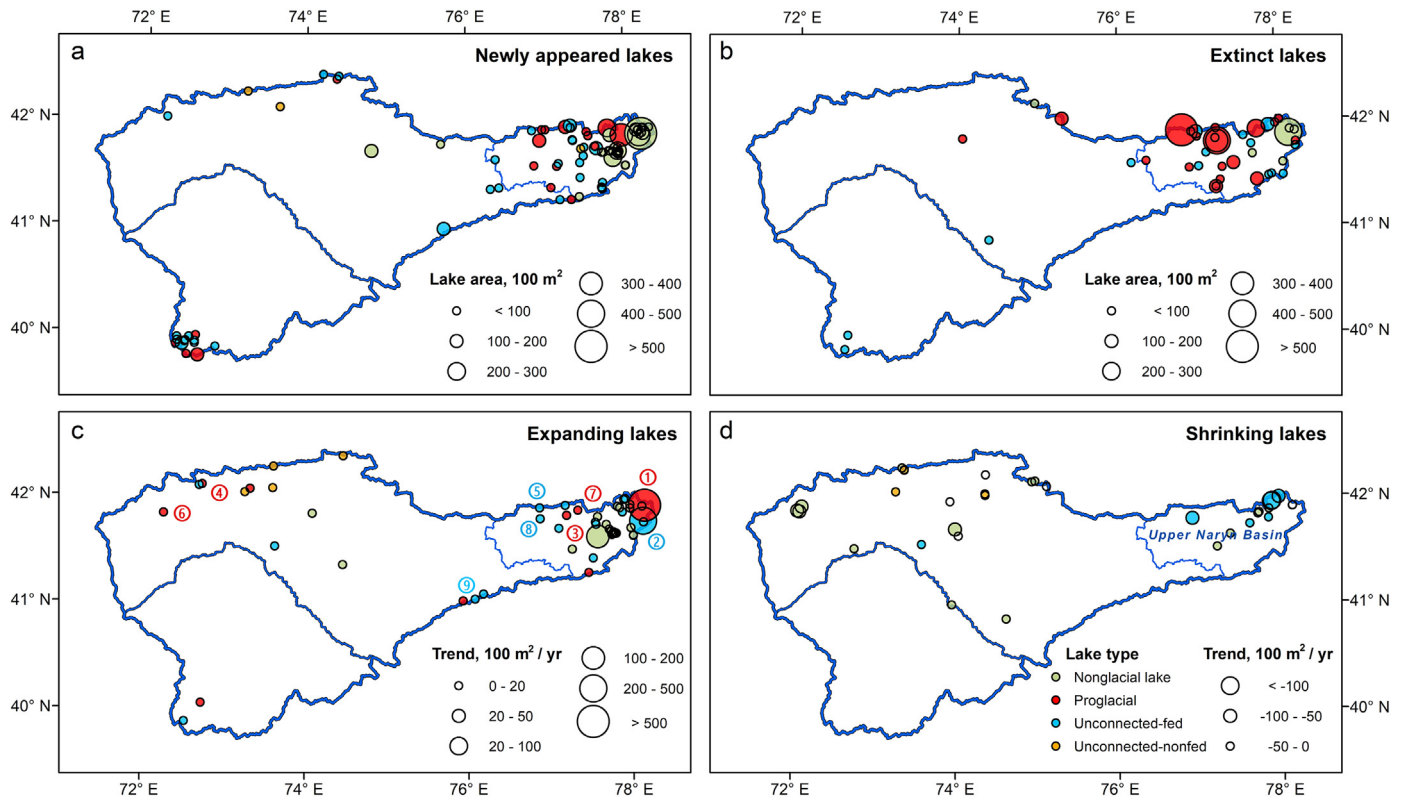


Fig. 9. Lake dynamics in the headwaters of the Syr Darya River between the 1990s and 2015. (a) Newly appeared lakes; (b) extinct lakes; (c) expanding lakes with positive linear trends ($p < 0.1$); and (d) shrinking lakes with negative linear trends ($p < 0.1$). The circled numbers in figure (c) show the locations of the glacial lakes in Fig. 11, and the different colours represent the corresponding lake type.

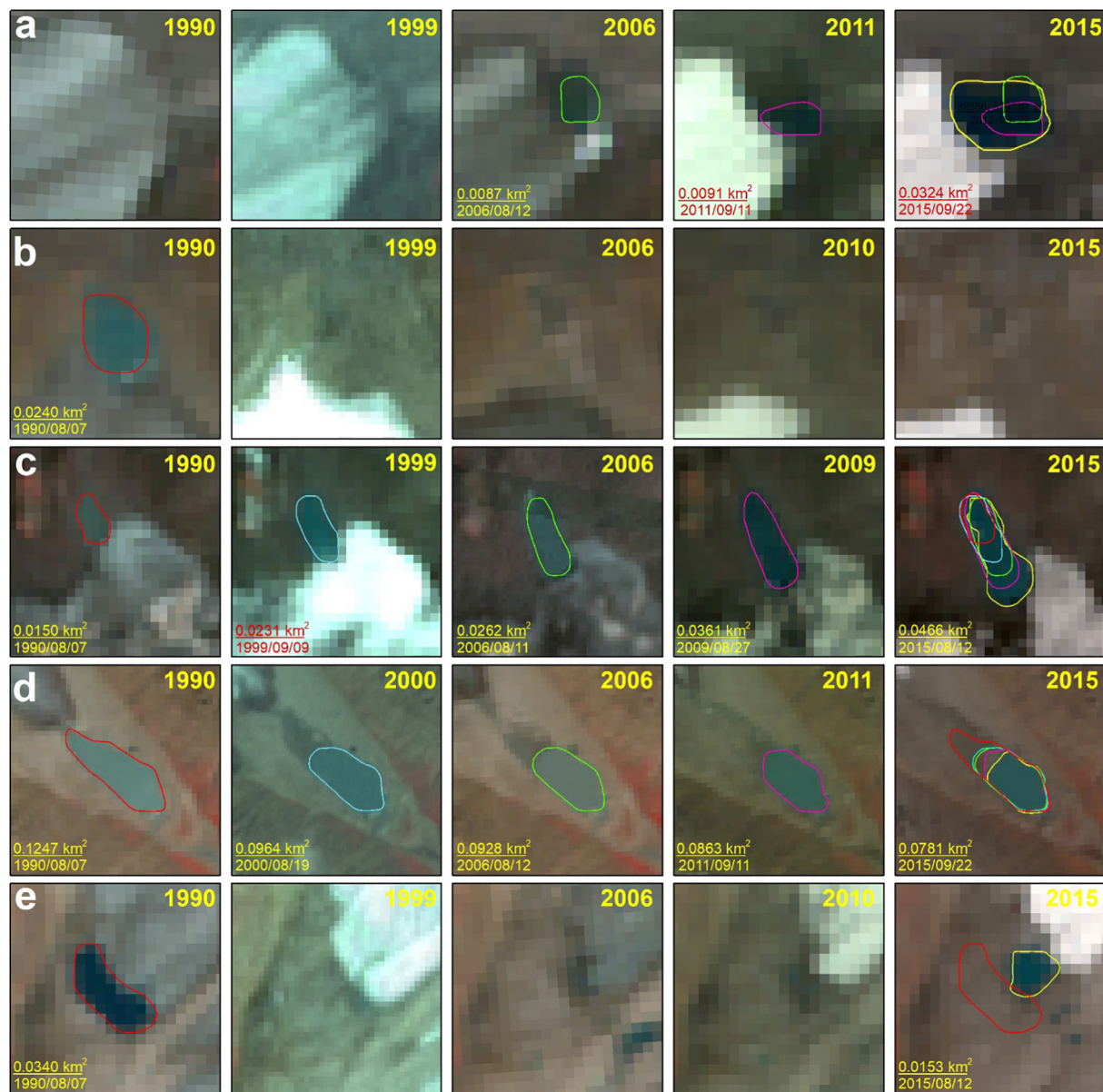


Fig. 10. Examples of different glacial lake evolutions. (a) newly appeared lake (41.843°N, 77.949°E); (b) extinct lake (41.919°N, 77.746°E); (c) expanding lake (41.836°N, 77.262°E); (d) shrinking lake (41.964°N, 77.950°E); and (e) irregular lake (42.017°N, 78.009°E). The background is Landsat false colour composite imagery (NIR, Red, Green bands as RGB). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

lakes in these areas, especially those near glaciers, are rarely disturbed by human activities. Hence, changes in these lakes are more attributed to changes in climate factors. For example, the increase in air temperature accelerates the melting of glaciers and snow cover, which in turn leads to the expansion of the glacial lake at its terminal and downstream. In contrast, nonglacial lakes at low altitudes are not only affected by changes in climatic factors, but also integrate the interference of human activities. Over the past decades, air temperatures have experienced increases in most regions of Central Asia, similar to the global trends (Sorg et al., 2012). According to the projection of the fourth IPCC report (and confirmed by the AR5), the average annual temperatures in Central Asia are expected to rise 2 °C by 2022 and 4–5 °C by 2100 relative to 1986–2005 (Bates et al., 2008). The analysis based on the CRU dataset shows that the air temperatures at the source of the Syr Darya River have obviously increased over the past 25 years, with an average increase of 0.04 °C yr⁻¹ (Fig. 12a). Moreover, a roughly consistent spatial pattern of temperature rise is observed in this region, whereas the annual increase in the western Tian Shan

Mountains is slightly higher than the eastern Fergana Valley. The records from three weather stations confirmed this increasing trend, but the CRU dataset evidently underestimates the growth trend of temperature in high altitude areas when comparing the observations from the Tian Shan station, which recorded a growth rate of 0.1 °C yr⁻¹ ($r = 0.76$, $p < .01$) from 1990 to 2015. The temperature growth rate according to the Tian Shan, Naryn and Dzhalal-Abad stations was 0.008 °C, 0.017 °C, 0.018 °C yr⁻¹, respectively, in the longer records of 1965–1990. The warming summer temperature resulted in a longer melting season, and glaciers in the Syr Darya River catchment declined from 121 km³ in the 1960s and 1970s to 101 km³ in 2000 (UNDP, 2009). In general, the glacier shrinkage in Tian Shan Mountains, Central Asia, is pervasive as recent climate change continues (Farinotti et al., 2015; Narama et al., 2010; Shangguan et al., 2015). The estimation of glacier mass balance in central Tian Shan Mountains revealed that the highest glacier mass loss accompanied by the most obvious glacier retreat occurred in the Ak-shiirak massif with a mass balance of -0.51 ± 0.36 m w.e.a⁻¹ and a rate of area change of

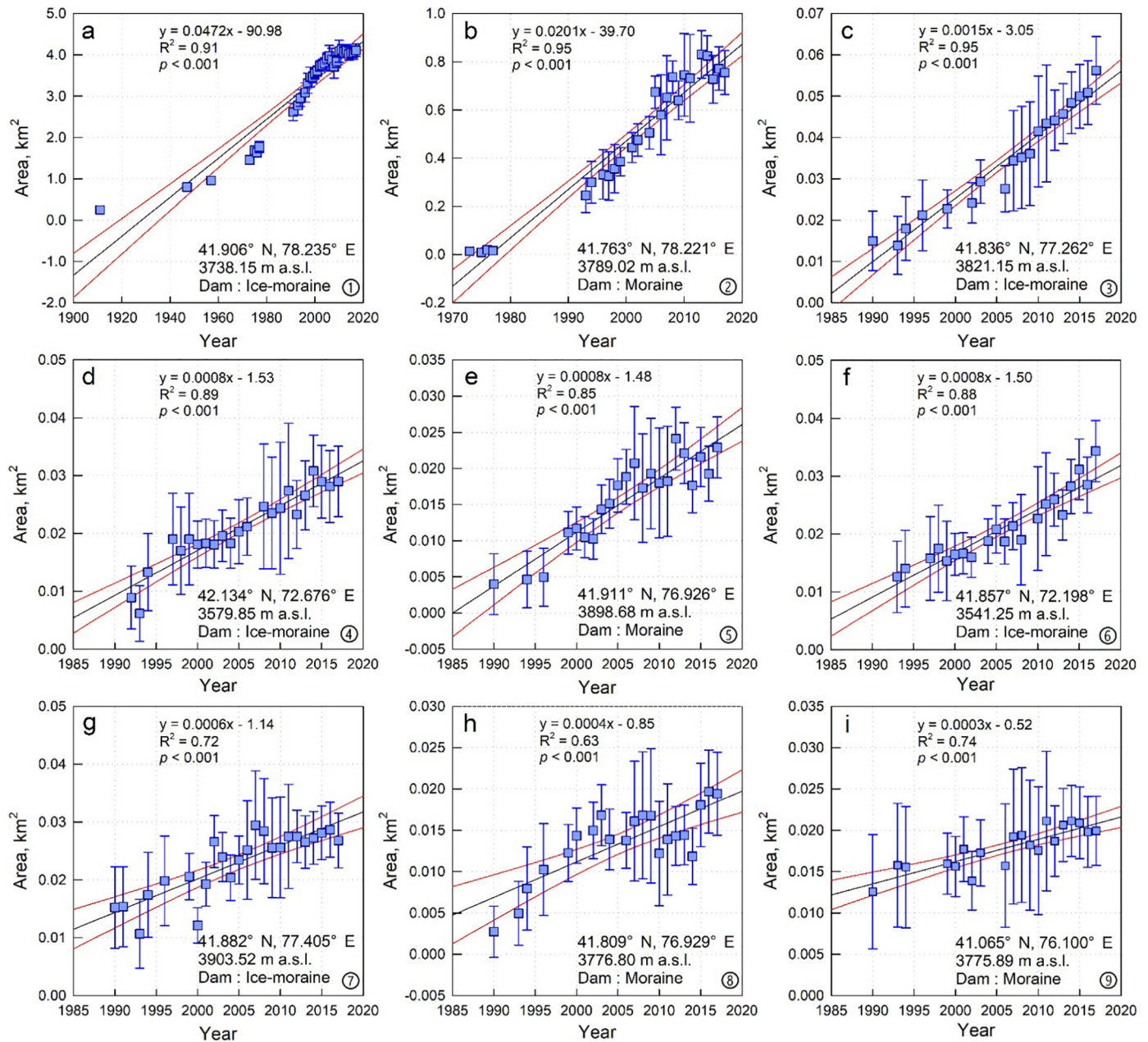


Fig. 11. Area change trends of nine rapidly growing glacial lakes in descending order according to the lake area growth rate ($p < 0.05$). The locations and serial numbers of each lake are shown in Fig. 9c. The error bars represent the uncertainty of lake area measurements. The red curves are the 95% confidence interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$-0.27 \pm 0.15\% \text{ a}^{-1}$ between ~1975 and 1999 (Pieczonka and Bolch, 2015). The recent inventory in the Ak-shiirak massif showed that the total glacier area lost $0.59 \pm 0.34\% \text{ a}^{-1}$ in 2003–2013, twice the rate of 1977–2003 and the summer warming is the main driver with a 7% contribution from the open pit mining of Kumtor Gold Mine (Petrakov et al., 2016). In addition, the snow cover duration is likely to decrease due to the reduction in solid precipitation and an earlier, more intense snowmelt is likely to occur because of the increased air temperature (Sorg et al., 2014).

Clear spatial heterogeneity in precipitation change was observed in the headwaters of the Syr Darya River (Fig. 12b). Based on the CRU dataset, precipitation shows a positive trend in the eastern high altitude areas and a negative trend is observed in the western low altitude regions. This is also confirmed by data from the three stations with records during 1990–2000/2005 (Fig. 12b). From the longer time scale

(after 1965), the change rates in precipitation at the Tian Shan, Naryn, and Dzhalal-Abad stations are -0.97 , 0.25 and 1.34 mm yr^{-1} , respectively. In general, the cryosphere fluctuation caused by climate warming has affected the lake dynamics during the observation period, mainly relating to the emergence of new glacial lakes and the expansion of existing lakes.

4.2. Sources of uncertainty

Data-driven uncertainty primarily results from the spatial resolution of the imagery. In this study, the total uncertainty of the lake area measurements using Landsat datasets for all five periods is 37.85 km^2 (or 2.33%). The total uncertainty based on the pan-sharpened Landsat OLI images in 2015 is 1.68%, which is 1.20% and 1.52% less than Landsat TM for lake extent extraction in the 1990s and 2010,

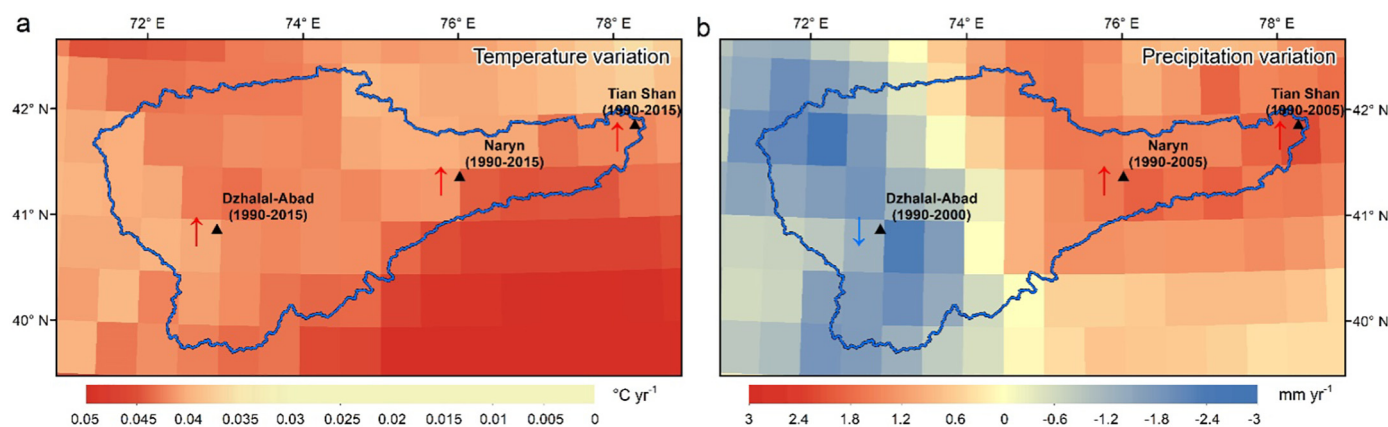


Fig. 12. (a) Temperature and (b) precipitation variations in the headwaters of the Syr Darya River between 1990 and 2015 derived from CRU TS v4.01 gridded data. The red and blue arrows in the graphs indicate the trends of temperature and precipitation based on the measured site records. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

respectively. In general, the uncertainty of the lake extent delineation using satellite scenes is inversely proportional to the spatial resolution of the images used. Method-driven uncertainty depends more on the knowledge of the interpreter in this field and the accuracy of the lake extraction algorithm. At present, the methods of lake boundary extraction mainly include automatic or semi-automatic extraction and manual visual delineation. Automatic or semi-automatic methods need to first distinguish the water body from other land types and then identify lakes from these water bodies, which is very effective for large lake extent extraction and large-scale lake mapping. However, since the lakes in the high mountains are easily disturbed by clouds, snow and topographic shadows, and the lakes in these regions (such as glacial lakes) are relatively small in size, manual interpretation is still the most common method (e.g. Cook et al., 2016; Emmer et al., 2016; Emmer et al., 2015; Narama et al., 2017; Zhang et al., 2015). In this study, all lakes were carefully identified and outlined manually by a single expert, although this was time-consuming and laborious. In addition, there remains no popularly recognized algorithm to quantitatively evaluate this uncertainty, although many algorithms have been proposed. For example, Hanshaw and Bookhagen (2014) assumed that lake area measurement errors were Gaussian, i.e., that $\sim 69\%$ (1σ) of pixels were subject to errors, and Wang et al. (2013) estimated errors based on ± 1 -pixel lake extent. Here, we used ± 0.5 pixels on either side of the outlined lake boundaries to assess the errors due to its widespread use (Petrov et al., 2017; Zhang et al., 2017b). Even so, these methods have larger error estimations for small lakes than for large lakes at the same spatial resolution, which will lead to overestimation for smaller lakes. Hence, an improved algorithm, especially for the evaluation of small glacial lakes, is still urgently required (Nie et al., 2017).

The uncertainty of lake type differentiation mainly comes from the principles and definitions of the lake classification system and lake distinguishability in satellite imagery. Internationally, there is currently no universally accepted standard lake classification system, particularly for glacial lakes (Yao et al., 2018). Without regard for the mechanical and thermal differences of glacial lake formation, formation age and the properties of the dam, glacial lakes are generally divided into five types: supraglacial lakes, en/subglacial lakes, proglacial lakes, unconnected-fed lakes and unconnected-nonfed lakes, which only consider the spatial and hydrologic relation between a glacial lake and its supplying glacier. The proglacial lakes usually include these lakes situated in the lateral areas of glaciers. The existence of en/subglacial lakes is reliable, especially in the Antarctic, the Arctic and large ice sheet covered areas (Livingstone et al., 2013; Oswald and Robin, 1973; Rutishauser et al., 2018). However, because of invisibility in optical satellite images, en/subglacial lakes are often discarded in most glacial lake studies (Nie et al., 2017; Wang et al., 2013; Wang et al., 2016). The distinction of

the type of supraglacial and proglacial lakes does not produce much uncertainty due to their clear positional relationship with the glacier in optical satellite images. The greatest uncertainty in the classification of glacial lake types arose in the last two types due to the widespread existence of subsurface supply channels (Narama et al., 2018; Shangguan et al., 2017), which could result in overestimation of unconnected-nonfed lakes and underestimation of unconnected-fed lakes. In this study, multitemporal and multisensor satellite images were used with the aid of high-resolution Google Earth™ images and 30-m SRTM DEM data to minimize the uncertainty in the distinction between the two lake types (Zhang et al., 2015). In addition, since the number of supraglacial lakes greater than the minimum mapping unit in this region is very few (only one was identified in the 1990s and 2010, two in 2015) coupled with their strong seasonal variations, these few supraglacial lakes were classified into the proglacial lake during the analysis.

The uncertainty in dynamic evolution analysis of lakes could arise from the integration of the lake area measurement errors and the statistical approaches used. The impact of lake type classification can be ignored due to its definition is consistent at different periods. Lake area change rate and linear regression method were often used to reveal the dynamic characteristics of the evolution of different lake types because these methods are intuitional and reliable (Wang et al., 2013; Zhang et al., 2015). The linear regression analysis was executed only for the lakes that existed and appeared in all five periods in this study. The uncertainty caused by the identification of new and disappearing lakes is generally controlled by the selected minimum mapping unit. For examples, Ma et al. (2010) and Zhang et al. (2019) have determined the new and extinct lakes based on the selected minimum mapping unit, which would cause much uncertainty. In this study, we considered the situation in which the lake area is less than the minimum mapping unit by adding extra fields during analysis based on the visual identifiability from satellite scenes. Moreover, multiperiod lake datasets combined with multitemporal satellite imagery can reduce the uncertainty in the detection of new and extinct lakes.

4.3. Potential impacts of lake changes

The observed growth trends in high-mountain lakes at the headwaters of Syr Darya River over the past 25 years are similar to that of the lake changes in most other adjacent areas, such as Tian Shan Mountains (Daiyrov et al., 2018; Wang et al., 2013), Tibetan Plateau (Song et al., 2016; Zhang et al., 2015) and Himalayas (Aggarwal et al., 2017; Nagai et al., 2017; Nie et al., 2017). In the short term, the expansion of lakes caused by increased glacial meltwater and the increase of lake volume has a certain effect on alleviating regional water

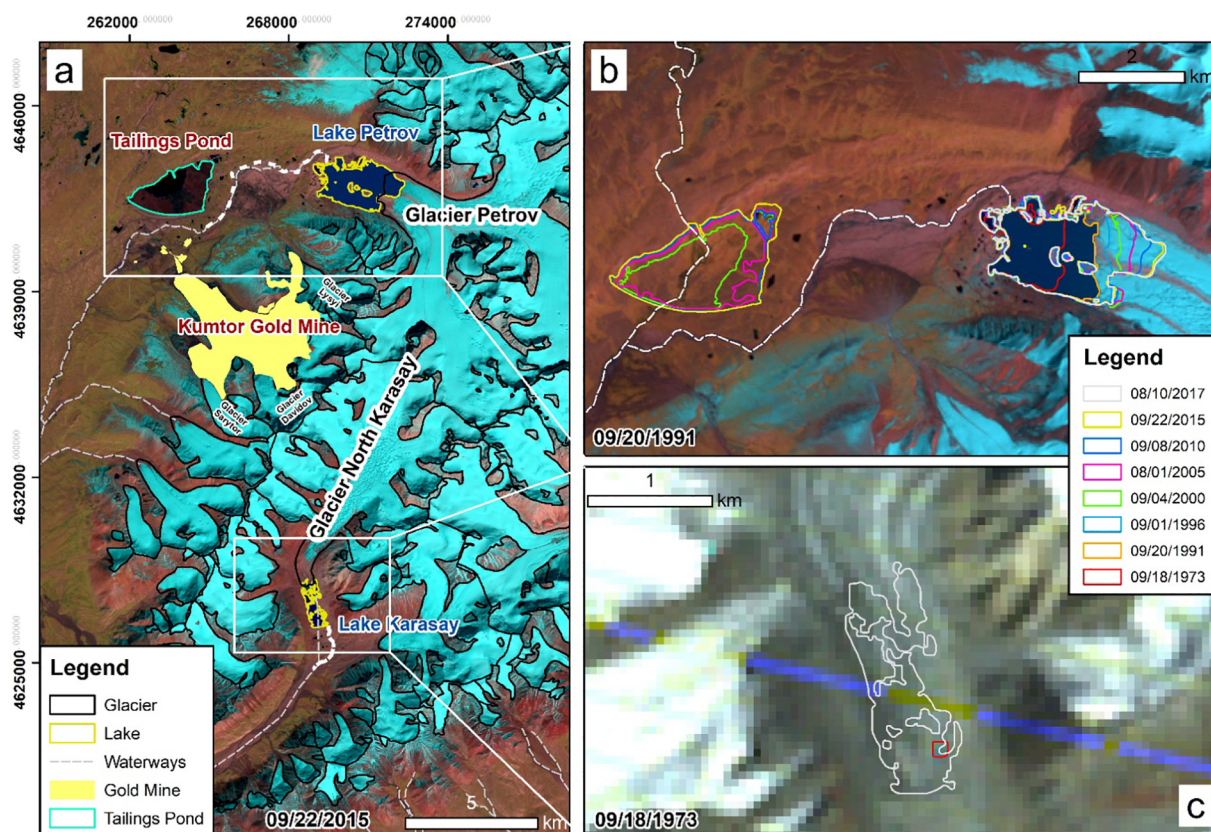


Fig. 13. Spatiotemporal development of the Lake Petrov, Lake Karasay and the tailings pond of the Kumtor Gold Mine. The thick dashed line in figure (a) is the superficial outflow of lakes, and the thin dashed line in figure (b) is the original flow routes of surface streams before the tailings pond appeared. The background is Landsat false colour composite image (NIR, Red and Green bands as RGB). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

shortages. However, as global warming causes the mountain glaciers to retreat or disappear further, small lakes near the glaciers (mainly glacial lakes) that rely primarily on glacial meltwater might first expand due to increased glacial meltwater, and then shrink as the supply glaciers recede. In addition, some of the proglacial lakes will gradually transform into unconnected-fed lakes and then further into unconnected-nofed lakes due to the continued retreat of the glaciers (Emmer et al., 2015). For low-altitude lakes with precipitation, river runoff, or mixed recharge with precipitation and glacial meltwater, their changes are relatively complex due to disturbances in human activities (Zhang et al., 2019). However, in general, if the air temperature continues to rise in the future, the lake surface evaporation and land surface evapotranspiration will increase, and the lake area will shrink and lake water will salt, which will be detrimental to the development of lake fisheries and the improvement of the ecological environment in the region. Moreover, although water volume stored in the glacial lake is relatively small, it is also an important source of fresh water in the region, which is of great value for regulating the status of hydrological resources in the region (Wang et al., 2013).

The continuous expansion of the glacial lake will increase the risk of potential GLOFs. However, the development and occurrence of GLOFs is a complex dynamic process involving a lot of impact and triggering factors such as glacier fluctuations and extreme weather events (Koungkoulos et al., 2018), and one of the important dynamical changes is the formation and growth of the glacial lakes associated with climate warming (Harrison et al., 2018). Research on GLOFs over the past few decades show an increasing trend in the context of widespread glacier retreat in most parts of the world (Emmer, 2018). During the past decade, many GLOF events or high-risk glacial lake outburst threats sourced in the Tian Shan Mountains have been reported (Bolch et al.,

2011; Falatkova et al., 2018; Kapitsa et al., 2017; Shangguan et al., 2017). More than 70 GLOFs events have been recorded in Kyrgyzstan alone since 1952 (Jansky et al., 2010). In the headwaters of the Syr Darya River, proglacial Lake Petrov presents a potential burst threat due to its rapid enlargement rate and poorly consolidated, ice-cored moraine dam. The growth of Lake Petrov has been enhanced by both the recession and melt of the Glacier Petrov. The results from Engel et al. (2012) indicated that the Glacier Petrov experienced an accelerated retreat from 1977 to 2009, and the largest shrinkage occurred in 1990–1995, with a recession rate of $54 \pm 8 \text{ m yr}^{-1}$. The accelerated downturn resulted in a clear expansion of Lake Petrov (Fig. 13b) and potential rupture risk of the dam. The dam stability of the lake is crucial for the downstream Kumtor tailings ponds, where nearly 60 million tons of cyanide liquid wastes have been collected and stored by 2015 (Kutmanova and Satke, 2015). The size of this tailing ponds is 4.0 km^2 in 2015; however, it did not exist in 1991 (Fig. 13b) because the Kumtor Gold Mine began production in 1997. Dam failure of the Kumtor tailings pond represents a rapid spilling of highly toxic wastewater and sediment into the Kumtor River, endangering downstream people, facilities, and even ecosystems and impacting downstream rivers throughout much of the Naryn River basin, which flows into Uzbekistan. Although some previous studies have collected a certain amount of data regarding the Lake Petrov (Jansky et al., 2008; Jansky et al., 2010) and its supply glacier (Petrakov et al., 2016), more focuses should be placed on the lake because of its continuous expansion in size and volume (Fig. 11a and Fig. 13b). Furthermore, another fast-growing glacial lake (Lake Karasay) was detected, which is situated in the terminus of the Glacier North Karasay in the Ak-shiirak massif and showed an area expansion rate of $0.02 \text{ km}^2 \text{ yr}^{-1}$ between 1973 and 2017 (Fig. 11b and Fig. 13c). Lake Karasay was also dammed by a system of

end moraines and surrounded downstream by several thermokarst lakes. Glacial meltwater from six glaciers flows into Lake Karasay, and the main source glacier, Glacier North Karasay, borders the Glacier Petrov in the north. Its superficial outlet is situated in the lower right of the lake (Fig. 13a). In comparison with Lake Petrov, Lake Karasay has received little research focus. However, due to the enlargement of the lake size and volume together with the instability of the moraine dam and its location in the upstream of the Naryn River, more research focuses should also be placed on this lake.

5. Conclusion

In this study, a detailed and comprehensive high mountain lake inventory was conducted for the upper catchment of the Syr Darya River based on historical Landsat remote sensing observations during the 1990s–2015. A significant growth trend in the number and size of lakes was observed during this period. Proglacial lakes had the highest relative average area change rate among the four lake types. The analysis of lake area change indicates that small lakes have greater volatility than large lakes. The spatial development of glacial lakes shows a shift to higher altitude areas; for instance, the average altitude of the proglacial lakes in the study area has increased by 62 m between 1990s and 2015. 91 new lakes and 54 disappeared lakes were identified in the study area. The enlargements of lakes, especially proglacial lakes, further confirm that the recession of glaciers in the sources of the Syr Darya River continues. Our multitemporal lake survey datasets can be integrated with other datasets, such as GLOWABO (Verpoorter et al., 2014), to analyse the lake dynamics in the larger-scale regions. Further work will focus on the GLOFs hazard and risk assessments and detailed investigation of high-risk glacial lakes in the region.

Acknowledgements

This work was supported by the Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDA20030101), the International Partnership Program of Chinese Academy of Sciences (Grant No. 131551KYSB20160002) and the National Key Research and Development Program of China (Grant No. 2016YFC0500201-02). We appreciate the U.S. Geological Survey (USGS) for allowing free access to their Landsat archives. The CRU v4.01 data variables were downloaded from <https://crudata.uea.ac.uk/cru/data/hrg/>. The GSOD dataset was provided by NOAA (<ftp://ftp.ncdc.noaa.gov/pub/data/g sod/>). We thank Adam Emmer and an anonymous reviewer for their constructive comments which have improved this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gloplacha.2019.03.004>.

References

Aggarwal, S., Rai, S.C., Thakur, P.K., Emmer, A., 2017. Inventory and recently increasing GLOF susceptibility of glacial lakes in Sikkim, Eastern Himalaya. *Geomorphology* 295, 39–54.

Bates, B., Kundzewicz, Z.W., Wu, S., Palutikof, J., 2008. *Climate Change and Water*. IPCC Secretariat, Geneva.

Bocchiola, D., Pelosi, M.G., Soncini, A., 2017. Effects of hydrological changes on co-operation in transnational catchments: the case of the Syr Darya. *Water Int.* 42 (7), 852–873.

Bolch, T., et al., 2011. Identification of potentially dangerous glacial lakes in the northern Tien Shan. *Nat. Hazards* 59 (3), 1691–1714.

CAD, 2010. *Alpine Exploration in Central Asia*, Central Asia Database. <http://www.webpages.uidaho.edu/cae/data/>, Accessed date: 1 April 2018.

Chen, F.H., Huang, W., 2017. Multi-scale climate variations in the arid Central Asia. *Adv. Clim. Chang. Res.* 8 (1), 1–2.

Chen, Y., Li, W., Deng, H., Fang, G., Li, Z., 2016. Changes in Central Asia's Water Tower: past, present and future. *Sci. Rep.* 6 (1), 35458.

Chen, F., Zhang, M.M., Tian, B.S., Li, Z., 2017. Extraction of Glacial Lake Outlines in Tibet Plateau using Landsat 8 Imagery and Google Earth Engine. *IEEE J. Select. Top. Appl.*

Earth Observ. Remote Sens. 10 (9), 4002–4009.

Cook, S.J., Koukoulos, I., Edwards, L.A., Dortch, J., Hoffmann, D., 2016. Glacier change and glacial lake outburst flood risk in the Bolivian Andes. *Cryosphere* 10 (5), 2399–2413.

Daiyrov, M., et al., 2018. Regional Geomorphological Conditions Related to recent changes of Glacial Lakes in the Issyk Kul Basin, Northern Tien Shan. *Geosciences* 8 (3), 99.

Emmer, A., 2018. GLOFs in the WOS: bibliometrics, geographies and global trends of research on glacial lake outburst floods (Web of Science, 1979–2016). *Nat. Hazards Earth Syst. Sci.* 18 (3), 813–827.

Emmer, A., Merkl, S., Mergili, M., 2015. Spatiotemporal patterns of high-mountain lakes and related hazards in western Austria. *Geomorphology* 246, 602–616.

Emmer, A., Klimes, J., Mergili, M., Vilimek, V., Cochachin, A., 2016. 882 lakes of the Cordillera Blanca: an inventory, classification, evolution and assessment of susceptibility to outburst floods. *Catena* 147, 269–279.

Engel, Z., Sobr, M., Yerokhin, S.A., 2012. Changes of Petrov glacier and its proglacial lake in the Akshirak massif, central Tien Shan, since 1977. *J. Glaciol.* 58 (208), 388–398.

Falatkova, K., Šobr, M., Janský, B., Neureiter, A., Schöner, W., 2018. Development of glacial lakes and evaluation of related outburst hazard at Adygine glacier complex, Northern Tien Shan. *Earth Surface Dyn. Discussions* 1–29.

Farinotti, D., et al., 2015. Substantial glacier mass loss in the Tien Shan over the past 50 years. *Nat. Geosci.* 8 (9), 716–722.

Feyisa, G.L., Meilby, H., Fensholt, R., Proud, S.R., 2014. Automated Water Extraction Index: a new technique for surface water mapping using Landsat imagery. *Remote Sens. Environ.* 140, 23–35.

Fujita, K., Sakai, A., Nuimura, T., Yamaguchi, S., Sharma, R.R., 2009. Recent changes in Imja Glacial Lake and its damming moraine in the Nepal Himalaya revealed by in situ surveys and multi-temporal ASTER imagery. *Environ. Res. Lett.* 4 (4), 045205.

Guo, H., et al., 2018. Spatial and temporal characteristics of droughts in Central Asia during 1966–2015. *Sci. Total Environ.* 624, 1523–1538.

Haemmig, C., et al., 2014. Hazard assessment of glacial lake outburst floods from Kyagar glacier, Karakoram mountains, China. *Ann. Glaciol.* 55 (66), 34–44.

Hanshaw, M.N., Bookhagen, B., 2014. Glacial areas, lake areas, and snow lines from 1975 to 2012: status of the Cordillera Vilcanota, including the Quelccaya Ice Cap, northern Central Andes, Peru. *Cryosphere* 8 (2), 359–376.

Harris, I., Jones, P.D., Osborn, T.J., Lister, D.H., 2014. Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset. *Int. J. Climatol.* 34 (3), 623–642.

Harrison, S., et al., 2018. Climate change and the global pattern of moraine-dammed glacial lake outburst floods. *Cryosphere* 12 (4), 1195–1209.

Janský, B., et al., 2008. The evolution of Petrov lake and moraine dam rupture risk (Tien-Shan, Kyrgyzstan). *Nat. Hazards* 50 (1), 83–96.

Janský, B., Sobr, M., Engel, Z., 2010. Outburst flood hazard: Case studies from the Tien-Shan Mountains, Kyrgyzstan. *Limnologia* 40 (4), 358–364.

Kapitsa, V., Shahgedanova, M., Machguth, H., Severskiy, I., Medeu, A., 2017. Assessment of evolution and risks of glacier lake outbursts in the Djungarskiy Alatau, Central Asia, using Landsat imagery and glacier bed topography modelling. *Nat. Hazards Earth Syst. Sci.* 17 (10), 1837–1856.

Komatsu, T., Tsukamoto, S., 2017. Late Glacial Lake-Level Changes in the Lake Karakul Basin (a Closed Glacierized-Basin), eastern Pamirs, Tajikistan. *Quat. Res.* 83 (01), 137–149.

Koukoulos, I., et al., 2018. Use of multi-criteria decision analysis to identify potentially dangerous glacial lakes. *Sci. Total Environ.* 621, 1453–1466.

Kutmanova, D., Satke, R., 2015. *Dam Spill Threats at a Gold Mine in Kyrgyzstan*. <http://glacierhub.org/2015/02/17/a-risk-of-a-dam-spill-threatens-a-large-gold-mine-in-the-mountains-of-kyrgyzstan/>, Accessed date: 1 April 2018.

Lehner, B., Grill, G., 2013. Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. *Hydrol. Process.* 27 (15), 2171–2186.

Li, J.L., Sheng, Y.W., 2012. An automated scheme for glacial lake dynamics mapping using Landsat imagery and digital elevation models: a case study in the Himalayas. *Int. J. Remote Sens.* 33 (16), 5194–5213.

Livingstone, S., Clark, C., Woodward, J., Kingslake, J., 2013. Potential subglacial lake locations and meltwater drainage pathways beneath the Antarctic and Greenland ice sheets. *Cryosphere* 7 (6), 1721–1740.

Ma, R.H., et al., 2010. A half-century of changes in China's lakes: Global warming or human influence? *Geophys. Res. Lett.* 37 (24), L24106.

Matsuoka, A., Babin, M., Devred, E.C., 2016. A new algorithm for discriminating water sources from space: a case study for the southern Beaufort Sea using MODIS Ocean color and SMOS salinity data. *Remote Sens. Environ.* 184, 124–138.

Mergili, M., Müller, J.P., Schneider, J.F., 2013. Spatio-temporal development of high-mountain lakes in the headwaters of the Amu Darya River (Central Asia). *Glob. Planet. Chang.* 107, 13–24.

Nagai, H., et al., 2017. Evaluating the Scale and potential of GLOF in the Bhutan Himalayas using a Satellite-based Integral Glacier–Glacial Lake Inventory. *Geosciences* 7 (3).

Narama, C., Kaab, A., Duishonakunov, M., Abdrakhmatov, K., 2010. Spatial variability of recent glacier area changes in the Tien Shan Mountains, Central Asia, using Corona (similar to 1970), Landsat (similar to 2000), and ALOS (similar to 2007) satellite data. *Glob. Planet. Chang.* 71 (1–2), 42–54.

Narama, C., et al., 2017. Seasonal drainage of supraglacial lakes on debris-covered glaciers in the Tien Shan Mountains, Central Asia. *Geomorphology* 286, 133–142.

Narama, C., et al., 2018. Large drainages from short-lived glacial lakes in the Teskey Range, Tien Shan Mountains, Central Asia. *Nat. Hazards Earth Syst. Sci.* 18 (4), 983–995.

Nie, Y., et al., 2017. A regional-scale assessment of Himalayan glacial lake changes using

- satellite observations from 1990 to 2015. *Remote Sens. Environ.* 189, 1–13.
- Nuimura, T., et al., 2015. The GAMDAM glacier inventory: a quality-controlled inventory of Asian glaciers. *Cryosphere* 9 (3), 849–864.
- Ososkova, T., Gorelkin, N., Chub, V., 2000. Water resources of Central Asia and adaptation measures for climate change. *Environ. Monit. Assess.* 61 (1), 161–166.
- Oswald, G.K.A., Robin, G.D.Q., 1973. Lakes beneath the Antarctic Ice Sheet. *Nature* 245, 251–254.
- Pekel, J.F., Cottam, A., Gorelick, N., Belward, A.S., 2016. High-resolution mapping of global surface water and its long-term changes. *Nature* 540, 418–422.
- Petrakov, D., et al., 2016. Accelerated glacier shrinkage in the Ak-Shyirak massif, Inner Tien Shan, during 2003–2013. *Sci. Total Environ.* 562, 364–378.
- Petrov, M.A., et al., 2017. Glacial lake inventory and lake outburst potential in Uzbekistan. *Sci. Total Environ.* 592, 228–242.
- Pieczonka, T., Bolch, T., 2015. Region-wide glacier mass budgets and area changes for the Central Tien Shan between similar to 1975 and 1999 using Hexagon KH-9 imagery. *Glob. Planet. Chang.* 128, 1–13.
- Rounce, D.R., Watson, C.S., McKinney, D.C., 2017. Identification of Hazard and risk for Glacial Lakes in the Nepal Himalaya using Satellite Imagery from 2000–2015. *Remote Sens.* 9 (7).
- Rutishauser, A., et al., 2018. Discovery of a hypersaline subglacial lake complex beneath Devon Ice Cap, Canadian Arctic. *Sci. Adv.* 4 (4), eaar4353.
- Schone, T., Dusik, E., Illigner, J., Klein, I., 2018. Water in Central Asia: Reservoir monitoring with Radar Altimetry along the Naryn and Syr Darya Rivers. *Int. Symp. Earth Environ. Sci. Future Generat.* 147, 349–357.
- Semakova, E., Gunasekara, K., Semakov, D., 2015. Identification of the glaciers and mountain naturally dammed lakes in the Pskem, the Kashkadarya and the Surhandarya River basins, Uzbekistan, using ALOS satellite data. *Geomat. Nat. Hazards Risk* 7 (3), 1081–1098.
- Shangguan, D.H., et al., 2015. Mass changes of Southern and Northern Inylchek Glacier, Central Tien Shan, Kyrgyzstan, during similar to 1975 and 2007 derived from remote sensing data. *Cryosphere* 9 (2), 703–717.
- Shangguan, D.H., et al., 2017. Quick Release of Internal Water Storage in a Glacier leads to Underestimation of the Hazard potential of Glacial Lake Outburst Floods from Lake Merzbacher in Central Tien Shan Mountains. *Geophys. Res. Lett.* 44 (19), 9786–9795.
- Siegfried, T., et al., 2011. Will climate change exacerbate water stress in Central Asia? *Clim. Chang.* 112 (3–4), 881–899.
- Soliev, I., Wegerich, K., Kazbekov, J., 2015. The costs of Benefit sharing: Historical and Institutional Analysis of Shared Water Development in the Ferghana Valley, the Syr Darya Basin. *Water* 7 (6), 2728–2752.
- Song, C.Q., Sheng, Y.W., Ke, L.H., Nie, Y., Wang, J.D., 2016. Glacial lake evolution in the southeastern Tibetan Plateau and the cause of rapid expansion of proglacial lakes linked to glacial-hydrogeomorphic processes. *J. Hydrol.* 540, 504–514.
- Sorg, A., Bolch, T., Stoffel, M., Solomina, O., Beniston, M., 2012. Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). *Nat. Clim. Chang.* 2 (10), 725–731.
- Sorg, A., et al., 2014. Coping with changing water resources: the case of the Syr Darya river basin in Central Asia. *Environ. Sci. Pol.* 43, 68–77.
- Sun, W.H., Chen, B., Messinger, D.W., 2014. Nearest-neighbor diffusion-based pan-sharpening algorithm for spectral images. *Opt. Eng.* 53 (1), 013107.
- UNDP, 2009. Second National Communication of the Kyrgyz Republic to the United Nations Framework Convention on Climate Change. UNDP (United Nations Development Programme), Bishkek.
- Unger-Shayesteh, K., Vorogushyn, S., Merz, B., Frede, H.G., 2013. Introduction to "Water in Central Asia - Perspectives under global change". *Glob. Planet. Chang.* 110, 1–3.
- Verpoorter, C., Kutser, T., Tranvik, L., 2012. Automated mapping of water bodies using Landsat multispectral data. *Limnol. Oceanogr. Methods* 10 (12), 1037–1050.
- Verpoorter, C., Kutser, T., Seekell, D.A., Tranvik, L.J., 2014. A global inventory of lakes based on high-resolution satellite imagery. *Geophys. Res. Lett.* 41 (18), 6396–6402.
- Wang, X., et al., 2013. Changes of glacial lakes and implications in Tien Shan, Central Asia, based on remote sensing data from 1990 to 2010. *Environ. Res. Lett.* 8 (4), 044052.
- Wang, X., Liu, Q.H., Liu, S.Y., Wei, J.F., Jiang, Z.L., 2016. Heterogeneity of glacial lake expansion and its contrasting signals with climate change in Tarim Basin, Central Asia. *Environ. Earth Sci.* 75 (8), 696.
- Wegerich, K., Van Rooijen, D., Soliev, I., Mukhamedova, N., 2015. Water Security in the Syr Darya Basin. *Water* 7 (9), 4657–4684.
- White, C.J., Tanton, T.W., Rycroft, D.W., 2014. The Impact of climate Change on the Water Resources of the Amu Darya Basin in Central Asia. *Water Resour. Manag.* 28 (15), 5267–5281.
- Yao, X.J., Liu, S.Y., Han, L., Sun, M.P., Zhao, L.L., 2018. Definition and classification system of glacial lake for inventory and hazards study. *J. Geogr. Sci.* 28 (2), 193–205.
- Zhang, G.Q., Yao, T.D., Xie, H.J., Wang, W.C., Yang, W., 2015. An inventory of glacial lakes in the Third Pole region and their changes in response to global warming. *Glob. Planet. Chang.* 131, 148–157.
- Zhang, G.Q., et al., 2017a. Extensive and drastically different alpine lake changes on Asia's high plateaus during the past four decades. *Geophys. Res. Lett.* 44 (1), 252–260.
- Zhang, G.Q., Li, J.L., Zheng, G.X., 2017b. Lake-area mapping in the Tibetan Plateau: an evaluation of data and methods. *Int. J. Remote Sens.* 38 (3), 742–772.
- Zhang, G.Q., et al., 2017c. Automated water classification in the Tibetan Plateau using Chinese GF-1 WFV data. *Photogramm. Eng. Remote. Sens.* 83 (7), 509–519.
- Zhang, M.M., Chen, F., Tian, B.S., 2018. Glacial Lake Detection from GaoFen-2 Multispectral Imagery using an Integrated Nonlocal active Contour Approach: a Case Study of the Altai Mountains, Northern Xinjiang Province. *Water* 10 (4), 455.
- Zhang, G.Q., et al., 2019. Regional differences of lake evolution across China during 1960s–2015 and its natural and anthropogenic causes. *Remote Sens. Environ.* 221, 386–404.